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ON-BOARD LOG AND COORDINATE TRANSFORMATION FOR DETECTED OBJECTS ON THE SURFACE OF WATER

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ABSTRACT

Context. The relevance of the work is to the demand for UAV technologies with the integration of artificial intelligence in today's conditions.

Objective. The goal of the work is to develop a minimum working version of the UAV explorer and software for controlling the UAV data.

Method. The proposed mathematical description, which calculates the coordinates of the object, based on the dimensions of the original image from the camera, the dimensions of the image with which the neural network works, the angle of the field of view of the camera, the position of the UAV and the angles of roll, pitch and yaw, allows you to transfer the coordinates of the object, of the found NN, in the image to the geographical coordinates, thereby moving away from the rigid reference to the coordinates of the UAV.

Results. The problem of systematization of objects detected during the mission on the surface of water bodies was solved by creating a flight log, organizing interaction with a neural network, applying post-processing of recognized objects, mathematically transforming the coordinates of objects for display and visualization into geographic coordinates, thereby move away from the rigid reference to the coordinates of the UAV.

Conclusions. A workable logbook generation and storage system has been created, which takes into account the peculiarities of information presentation in the logbook, and ensures effective interaction of the components of the created information system within the proposed hardware and software complex, which allows organizing the process of researching water bodies using the SITL environment from the flight controller developers.

KEYWORDS: UAV, flight controller, mission log, neural network, geographic coordinates, recognized images, forecast accuracy, image post-processing.

ABBREVIATIONS

AI stands for artificial Intelligence;
FC is a flight controller;
DDPG is a deep deterministic policy gradient;
CTD is a conductivity temperature depth;
MPS is a multi-parameter sensor;
LiDAR is a light detection and ranging;
DEM is a digital elevation model;
GPS is a global positioning system;
RS is a remote sensing;
RPAS is a Remotely Piloted Aircraft Systems;
SfM is the Structure from Motion;
IAS is a image alignment settings;
KPL is a key point limit;
PID control is a proportional-integral-derivative control;
YOLO is the You Only Look Once;
COCO is a Common Objects in Context;
SPI is a serial peripheral interface;
NIOT is the National Institute of Ocean Technology;
MOES is the Ministry of Earth Sciences;
PFC is a compared, including fixed parameters;
PFC_FL is a parameters tuned using fuzzy logic,
IC is a information system;
UAV is a unmanned aerial vehicle;
BVLOS is a Beyond Visual Line of Sight;
DCNN is a deep convolution neural network;
DB is a database;
EMA is a Efficient Multi-Scale Attention;
GUI is a graphical user interface;
CycleGAN is a Cycle-Consistent Generative Adversarial Networks;
COTS is the Commercial Off-The-Shelf;
MIoU is the Mean Intersection over Union;
NMPC is a nonlinear model predictive control;
NN is a neural network.

NOMENCLATURE

A_p is a coordinates of the center of the rectangle in which the network detected the object;
w_s , h_s is a dimensions of the original image from the camera;
w_p , h_p is a dimensions of the image with which the neural network works;
FOV is a diagonal camera angle;
F_x, F_y is a viewing angles of the camera along the horizontal and vertical axes;
P is a yaw angle;
R is a pitch angle;
Y is a rotation of the resulting vector to the roll angle;
Alt is a UAV altitude (height);
N is a UAV latitude;
E is a UAV longitude;
°- is a binary operation that takes in two matrices of the same dimensions and returns a matrix of the multiplied corresponding elements. This operation can be thought as a "naive matrix multiplication" and is different from the matrix product;

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- •- the dot product or scalar product.

INTRODUCTION

The relevance of the project is due to the demand for UAV technologies with the integration of artificial intelligence in today's conditions.

The object of study is an information system for managing one UAV to perform geographic reconnaissance tasks and take biological or chemical water samples.

The process of forming and downloading the flight log from detected AI images for further processing of mission results and linking to geographic coordinates was investigated.

The subject of study is the implementation of AI technologies in the work of UAVs for the analysis of the state of water bodies, by organizing the interaction of UAVs with external (self-created) modules of the built information system.

The purpose of the work is to develop a minimum working version of the UAV-researcher and software for managing UAV data.

1 PROBLEM STATEMENT

Due to the war, limited material and personnel resources, extraordinary security requirements, it is necessary for this type of UAV to solve the problem of taking water from reservoirs near cities, mountainous regions, where it is difficult to send expeditions, and together with the proposed information system, perform tasks patrols using trained *AI* to detect poaching boats, areas with high concentrations of garbage or fishing net buoys on the surface of water bodies.

Given the coordinates of the drone (*N*, *E*, *Alt*), (*P*, *R*, *Y*) angles of the drone, the camera FOV expressed in degrees, (*ws*, *hs*), (*wp*, *hp*) and the *Ap*.

The task of finding the (*N*, *E*, *Alt*) of the detected object with an accuracy of the found coordinates optimization criterion with the following constraints on the input and output variables:

In asynchronous mode, after finding a certain image, the neural network of the RaspberryPi microcomputer calculates the corresponding geographical coordinates of the found object using the proposed mathematical transformations and forms a flight log.

The output variables are considered to be (*N*, *E*,, *Alt*), assuming the drone is moving over a flat water surface. *E* is limited to values between –180 and 180 degrees. *N* is bounded between –90 and 90 degrees. *Alt* can take any value in the range (-inf, inf). *FOV* must be within the range (0, 360] degrees. (*ws*, *hs*) must be greater than 0, bounded within (0, inf). (P, R, Y) angles are limited to values between –180 and 180 degrees. Coordinates *Ap* must be within the range [0, inf).

2 REVIEW OF THE LITERATURE

Path following is a critical challenge for small fixed-wing UAVs [1]. This study introduces a Lyapunov-stable path guidance law designed to follow specific planar curved paths. To ensure smoothness, a modified saturation function was developed for the guidance law. An analysis was conducted to explore the relationship between control parameters and input constraints, identifying the appropriate parameter ranges.

To optimize the guidance law parameters, the NMPC technique was applied, resulting in the PFC_NMPC method. This method enhances the UAV's performance in following both straight-line and circular paths. Using Lyapunov stability arguments for switched systems, the stability of the nonlinear switched system was ensured.

Square and circular paths were generated to evaluate the path-following control of a simulated fixed-wing UAV. Various guidance laws were compared, including those with PFC, parameters tuned using PFC_FL, PFC_NMPC, vector field, and pure pursuit with line-of-sight. The PFC_NMPC method demonstrated superior performance, achieving faster convergence to the desired path and maximizing the effective flight path length.

The study addresses [2] the challenge of maintaining high control performance for UAVs in harsh environments, focusing on trajectory tracking under wind disturbances, specifically average wind and wind shear. It highlights the need for timely disturbance compensation, which is often overlooked.

To enhance control accuracy and robustness, a novel antidisturbance sliding mode control is developed based on a reference model. This method includes the use of state compensation function observers to improve the estimation of states and disturbances that are difficult to measure directly. Additionally, a tracking differentiator is employed to estimate and compensate for disturbance variations, increasing the system's sensitivity to disturbances.

The proposed observer and controller's effectiveness and stability are analyzed. Verification is conducted through simulations and actual flights using multiple industrial fans to replicate average wind and wind shear conditions. The performance of the new method is compared to state-of-the-art active disturbance rejection control and sliding mode control. Results show that the new method improves accuracy by over 61.2% compared to these existing methods.

Heavy payload airdrops significantly alter flight dynamics, presenting a challenge for flight controller design [3]. This study addresses the control issues associated with aircraft performing heavy payload drops. A multi-equilibrium switched systems approach is employed to model the substantial changes in flight dynamics and trim points during such missions, particularly when payloads are released from non-central positions.

To ensure stability and minimize control bumps, a bumpless transfer switched controller is proposed. Unlike previous studies focusing on systems with a common equilibrium, this research extends stability conditions and bumpless transfer techniques to multi-equilibrium scenarios.

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Simulations and hardware-in-loop experiments validate the proposed method, demonstrating its effectiveness in maintaining flight control system stability and achieving smooth transitions during payload drops [4]. This method offers a robust solution for managing the complex dynamics involved in heavy payload airdrop missions.

This study introduces a trajectory tracking control method [4] for fixed-wing UAVs using DDPG. First, the trajectory control problem is integrated into a reinforcement learning framework and converted into a Markov decision process, with a DDPG agent implemented in TensorFlow.

Next, simulations were conducted to train and optimize the model in a 3D environment for trajectory tracking control, resulting in a comprehensive DDPG-based controller capable of managing the UAV's flight state and rudder control.

Finally, a digital simulation system was built to test the proposed method, taking into account parametric uncertainties, measurement noise, and control system response delays. The effectiveness and robustness of the DDPG controller were validated by comparing its performance with traditional PID control.

The Gobi Desert in southern Mongolia contains an exceptionally rich record of dinosaur and vertebrate fossils from the latest Cretaceous Period [5]. Over a dozen sites across various basins have yielded one of the world's most diverse palaeofaunas from this interval. Much of this diversity has been unearthed from the fluvial deposits of the Nemegt Formation. Despite extensive historical and ongoing research in southern Mongolia, accurate maps and detailed geological data for the main fossil sites are still lacking. This gap limits the ability to investigate how local palaeoecological dynamics influenced the distribution and evolutionary patterns of Nemegt taxa. One significant site, Guriliin Tsav, has yielded over a hundred notable fossil specimens but remains less studied compared to the nearby Bügiin Tsav, one of the most prolific Nemegt Formation localities. To address this, a project was initiated in 2018 to create a high-resolution topographic map of Guriliin Tsav using UAVs. This effort included plotting the geographic and stratigraphic distributions of palaeontological resources on the map. Additionally, stratigraphic and taphonomic data were collected, enabling the first detailed palaeoecological interpretation of Guriliin Tsav and comparison with other southern Mongolian localities. The results of this project, along with new topographic and stratigraphic data from Bügiin Tsav, are presented. These findings provide new insights into the temporal and geographic distribution of vertebrate taxa in the latest Cretaceous of Mongolia.

Drones, or UAVs, have gained significant importance worldwide for various commercial and defense applications [6]. The NIOT under the MOES is focusing on maritime applications of UAVs. A heavy-lift drone has been customized by NIOT for marine environments, capable of withstanding coastal wind conditions up to 40 kmph and carrying an instrumentation payload of 10 kg. This UAV can collect ocean data and perform seawater sampling. The payload may include a CTD sensor, a programmable seawater sampler, a MPS for ocean data collection, and a LiDAR device integrated with a high frame rate camera system for coastal mapping and DEM development. The hexacopter UAV can endure winds up to 10 m/s and features a waterproof IPX7 thruster with a maximum thrust of 153 N per axis. It is equipped with a GPS, a barometric pressure sensor, a compass, a highly accurate gyroscope, a 15 MP surveillance camera, and an accelerometer sensor, all connected to a reliable cube orange flight controller module with a redundant 32-bit controller via a SPI. The drone's structure and frame are made of carbon fiber composites, providing an excellent weight-to-strength ratio. Initial field tests were conducted to ensure the drone's suitability for various marine applications with payloads ranging from 5–10 kg, including coastal demonstrations and ocean data collections performed in the coastal waters of Nellore (Andhra Pradesh) and Chennai (Tamil Nadu).

Cracks serve as the primary indicators of the structural health of concrete structures [7]. Frequent inspection is essential for maintenance, and automatic crack inspection offers significant advantages in terms of efficiency and accuracy. Traditional image-based crack detection systems have been used for individual images, but they are not effective for inspecting large areas. Therefore, an image-based crack detection system using a DCNN is proposed to identify cracks in mosaic images composed of UAV photos of concrete footings. UAV images are transformed into 3D footing models, from which composite images are created. The CNN model is trained on 224 × 224 pixel patches, with training samples augmented through various image transformation techniques. The proposed method localizes cracks on composite images using the sliding window technique. The VGG16 CNN detection system, with a 95% detection accuracy, demonstrates superior performance compared to feature-based detection systems.

The fine-scale spatial heterogeneity of low-growth Arctic tundra landscapes requires high-resolution remote sensing data to accurately detect vegetation patterns [8]. Although multispectral satellite and aerial imaging, including UAVs, are commonly used, hyperspectral UAV imaging has not been thoroughly explored in these ecosystems. In this study, the added value of hyperspectral UAV imaging compared to multispectral UAV imaging was assessed for modeling plant communities in low-growth oroarctic tundra heaths in Saariselkä, northern Finland. Three different spectral compositions were compared: 4-channel broadband aerial images, 5-channel broadband UAV images, and 112-channel narrowband UAV images. Vascular plant aboveground biomass, leaf area index, species richness, Shannon's diversity index, and community composition were estimated based on field vegetation plot data. Spectral and topographic information were used to compile 12 explanatory datasets for random forest regression and classification. The highest R^2 values for aboveground biomass and leaf area index were found to be 0.60 and 0.65, respectively, with broad-

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band variables being the most important. In the best models for biodiversity metrics, species richness and Shannon's index had R^2 values of 0.53 and 0.46, respectively, with hyperspectral, topographic, and multispectral variables showing high importance. For four floristically determined community clusters, random forest classifications and fuzzy cluster membership regressions were conducted, with the overall accuracy for classification reaching 0.67 at best, and cluster membership estimated with an R^2 of 0.29–0.53. Variable importance depended heavily on community composition, with topographic, multispectral, and hyperspectral data all selected for these models. Hyperspectral models generally outperformed multispectral ones when topographic data were excluded. When topographic data were included, the performance difference was reduced, with hyperspectral data improving R^2 values by 0–10 percentage points, mainly in metrics with lower initial R^2 values. These findings suggest that while hyperspectral imaging can outperform multispectral imaging, multispectral and topographic data are generally sufficient for practical applications in tundra heaths

Coral reefs provide a range of ecological services and support highly diverse coastal ecosystems [9]. However, the extent of living corals has been reduced by half globally due to anthropogenic and natural stressors. Continuous monitoring using accessible RS methods to map coral habitats is necessary for effective conservation and management strategies. Recently, the use of RPAS for coral reef RS has increased. Image misalignment is considered a key problem in the SfM workflow. Combinations of IAS and KPL optimizations aim to improve the quality of the sparse cloud while lowering SfM reconstruction uncertainty, increasing projection accuracy, and ultimately improving coral habitat classification accuracy. Orthoimages were produced from a total of 25 combinations of IAS (lowest, low, medium, high, and highest) and KPL (5k, 10k, 20k, 40k, and 60k) using Agisoft™ Metashape software. Measurements of geometric distortion, efficiency, and completeness were used to evaluate these orthoimages with three visible bands. Results that satisfied the requirements for both geometric quality and spectral accuracy, as well as processing efficiency, identified the optimum alignment methods needed for routinely monitoring and mapping coral reefs of Pulau Bidong. The SfM-image alignment techniques chosen for this study produced a greater extent of coral mapping, a higher number of tie points and matches, better image alignment success and coral habitat classification accuracy, reduced processing time and memory usage, and no geometric distortions. The development of the methodology for the optimum parametrization of RPAS multispectral imagery would be beneficial to researchers studying coral reefs, marine sciences, and RS data analysts. Reliable methods for evaluating the quality of orthoimages and faster processing methods to achieve coastal RS objectives would be provided.

In the context of today's pressing air pollution challenges, accurate and consistent air pollution mapping is deemed crucial for understanding pollutant distribution and identifying pollution sources [10]. While current technologies, including sensors and UAVs, have started addressing this issue, the full potential of UAV-based solutions remains largely untapped. This pioneering numerical study demonstrates the effective feasibility of precise and consistent air pollution mapping in local areas that exceed the coverage capacity of a single UAV. The approach involves employing multiple UAVs, which requires rigorous mission planning encompassing various complex stages. These stages include subdividing the mapping area into manageable sub-areas, evaluating the technical capabilities of each UAV, assigning specific tasks to UAVs, and conducting individual mapping operations. By endowing UAVs with full autonomy, horizontal air pollution maps are generated across different layers within the designated area. This method's distinct advantage is its simultaneous acquisition of vertical profiles at all points within the study region, eliminating the need for additional efforts. Through strategic technical analysis, it was revealed that each UAV's mission coverage area could be expanded by over 30%, leading to more consistent air pollution mapping. Furthermore, this finding suggests a reduction of up to 25% in the total number of UAVs required for studies covering significantly larger areas.

Saltwater intrusion [11], a natural process of mixing freshwater from watersheds with seawater, is common in estuaries. Traditional station-based monitoring of saltwater intrusion is both time-consuming and labor-intensive. To facilitate rapid monitoring, this study devised new remote sensing algorithms for measuring water surface salinity, employing four decision tree-based machine learning models. These models were trained using in-situ salinity data collected concurrently with hyperspectral images from UAVs in the Pearl River Delta. A 10-fold cross-validation assessed model performance, with XGBoost emerging as the top performer ($R2=0.93$, $RMSE = 0.88$ psu). Subsequently, the developed model was applied to Sentinel-2 multispectral satellite images to estimate estuarine salinity distribution at a larger spatial scale. The results showcased the efficacy of the machine learning models proposed in this study for mapping salinity distribution in river channels, thus offering an efficient and practical approach for monitoring saltwater intrusion in river channels at a regional scale.

Peach cultivation is of significant economic importance, and obtaining the spatial distribution of peach orchards is crucial for yield prediction and precision agriculture. In this study, a new U-Net semantic segmentation model is introduced, utilizing ResNet50 as a backbone network and augmented with an EMA mechanism module and a LayerScale adaptive scaling parameter [12]. To address style differences between images from *UAV*, Google Earth, and Sentinel-2 satellite, CycleGAN are incorporated. This synthesis ensures that UAV images conform to a comparable style found in Google Earth and Sentinel-2 images, while feature details of high spatial resolution UAV images are transferred to Google Earth and Sentinel-2 images through transfer learning. The re-

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sults demonstrate that using ResNet50 as a backbone network for the U-Net model yields higher accuracy compared to using VGG16 for the U-Net model. Specifically, the MIoU values for UAV and Sentinel-2 images are higher by 0.49 % and 0.95 %, respectively. The MIoU values for UAV, Google Earth, and Sentinel-2 images increased by 0.87 %, 1.71 %, and 1.74 %, respectively, with the introduction of EMA. Additionally, with the introduction of LayerScale adaptive scaling parameters, the MIoU values increased by 0.31 %, 0.33 %, and 1.44 %, respectively, further enhancing the segmentation accuracy of the model. After applying CycleGAN and transfer learning, the MIoU increased by 1.02 %, 0.15 %, and 1.57 % for UAV, Google Earth, and Sentinel-2 images, respectively, resulting in MIoU values of 97.39 %, 92.08 %, and 84.54 %. The comparative analysis with DeepLabV3+, PSPNet, and HRNet models demonstrates the superior mapping performance of the proposed method. Moreover, the method exhibits good generalization and mapping speed across six test sites in the research area. Overall, this approach ensures high precision and efficiency in peach orchard mapping, accommodating various spatial resolutions, and holds potential for addressing diverse requirements in peach orchard mapping applications.

Cost-effective vision-based obstacle avoidance for UAVs operating in GPS-denied environments is discussed in this paper [13]. The system combines the YOLO architecture with stereo vision cameras (OAK-D Lite), a Raspberry Pi computer, and a flight controller unit (Pixhawk-Cube). Navigating safely through obstacles becomes challenging for UAVs in GPS-denied environments. To address this issue, the drone is configured in altitude hold mode, and the system is trained on the COCO dataset, enabling it to recognize objects and analyze the surrounding areas to identify free spaces. By doing so, the drone can traverse an obstacle-free path. The detected obstacle information is then utilized to generate avoidance trajectories, allowing the UAV to navigate around obstacles safely. Real-Time testing of the proposed technique demonstrates its efficacy in detecting and avoiding obstacles within a threshold distance of 2 meters, with an error rate of 10%. The drone’s relative speed is configured at 2 m/s during these tests.

In this paper [14], the focus lies on achieving precise position and attitude data for drones in GPS-denied environments by integrating SLAM to provide visual measurements for EKF, thereby ensuring operational stability. An experiment was conducted to execute commands from the ground control PC using the map created through SLAM. The primary tools utilized included the Pixhawk Orange, Jetson Nano, and the ZED-Mini camera. The research highlights the effectiveness of these tools and methods in improving indoor drone functionality.

At present [15], owing to the growing interest in UAVs and the continuous advancement of the UAV market and artificial intelligence technologies, this branch of robotics is increasingly penetrating various sectors of the economy. The rising popularity of fast and lightweight vehicles like UAVs has led to an increased demand for efficient flight path planning algorithms to achieve diverse objectives such as overflight, obstacle detection, and collision avoidance. Our algorithm achieves one of these objectives by navigating around static obstacles in 3D space using a sparse weighted graph. A hybrid method has been devised to determine the safest and fastest route based on Dijkstra’s algorithm, which operates with satellite images of various terrain classifications. The novelty of the proposed algorithm lies in the integration of artificial neural networks for terrain class categorization and utilizing this data in flight task planning. The concept involves charting a route over the safest terrain to ensure that in the event of an emergency descent or landing, the UAV remains locatable. This approach is more memory-efficient as it does not necessitate storing all vertices in an open list, unlike algorithms with similar functionality. Alongside the software architecture, the most suitable hardware architecture for the intended purpose – delivering cargo to challenging terrain – is presented.

This paper [16] introduces a novel software package named RoboPV for autonomous aerial monitoring of PV plants. RoboPV automates the aerial monitoring process, from optimal trajectory planning to image processing and pattern recognition for real-time fault detection and analysis. RoboPV comprises four integrated components: boundary area detection, path planning, dynamic processing, and fault detection. To design an optimal flight path, aerial images of PV plants are inputted to a developed encoder-decoder deep learning architecture to automatically extract boundary points. Then, a novel path planning algorithm is executed by RoboPV to design an optimal flight path covering the entire PV plant regions. A high-precision neural network trained for automatic fault detection analyzes aerial images in real-time during the flight. Several decision-making and maneuver algorithms are developed for various real-world flight conditions to enhance RoboPV’s performance during autonomous aerial inspection. RoboPV is a modular processing library installable on any micro-computer processor with low computational power. Additionally, support for the MAVLink communication protocol allows RoboPV to connect with an intelligent Pixhawk flight autopilot and navigate various multi-rotors. To demonstrate RoboPV’s performance, a six degrees of freedom dynamic model of a multi-rotor is developed in a SIMULINK environment with a defined aerial monitoring mission on three different real megawatt-scale PV plants. The results demonstrate that RoboPV can execute autonomous aerial inspection with an overall accuracy of 93% for large-scale *PV* plants.

The ADACORSA demonstrator focuses on implementing a fail-operational avionics architecture that combines COTS elements from the automotive, aerospace, and artificial intelligence sectors [17]. A collaborative sensor setup, including a Time-of-Flight camera and FMCW RADAR from Infineon Technologies, stereo camera, LiDAR, IMU, and GPS, facilitates testing of heterogeneous sensor fusion solutions. A Tricore Architecture on AURIX™ Microcontroller supports safety super-

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vision tasks and data fusion. An embedded computer platform (NVIDIA Jetson Nano) enhances AI algorithm performance and data processing. Additionally, an FPGA optimizes power consumption of Artificial Neural Networks. Lastly, a Pixhawk open-source flight controller ensures stabilization during normal flight operations and provides computer vision software modules for further processing of captured, filtered, and optimized environmental data. This paper presents various hardware and software implementations, showcasing their emerging application within BVLOS drone services.

Increasing productivity, reducing task completion time, scaling processing, excluding humans from the process of performing routine tasks, and ensuring online collection and processing of information are relevant for the operation of UAVs processes [18, 19].

The relevance of the project is due to the demand for UAV technologies with the integration of artificial intelligence in today's conditions in the direction of creating an on-board logbook and transforming coordinates for the detection of objects on the surface of water bodies.

3 MATERIALS AND METHODS

The process of patrolling the surface of reservoirs and determining and identifying objects on their surface is based on interaction with a neural network, the work, structure and learning process of which are described in detail in [20]. For the specified neural network, tools should be developed to create an on-board flight log and report on found objects. The Ultralytics API was chosen to interact with the model. It is worth noting that the OpenCV library was used for image processing, as its functionality allows you to switch from processing test data from the media to processing data from the camera.

During the development of the system, a problem arose: due to the reduction of the accuracy threshold for the neural network, it began to recognize one object as different objects of different classes.

In order to avoid this phenomenon, which would lead to the overflow of the local UAV storage with a large number of photos of the same object, it was decided to add a stage of post-processing of NM predictions, which will be based on an algorithm similar to the filtering algorithm already implemented in NM, which suppresses re-detection of the object by the network and is based on the area of intersection of the detected rectangles.

Accordingly, these results should be stored in the database as found objects. To perform this stage, the creation of a log using the tinydb library was implemented. Since this module does not support storing photos in the database, file names with unique identifiers will be used as record objects (Fig.1). Also, due to the remarks made in the AI training section, it would be logical to store the image from which the elements were extracted. As a result, it was possible to create logs for a completed mission using test images, which show that there is no duplication of information (Fig. 2).

One of the features of the information system of this project is that within this system there are simultaneously two subsystems (the UAV and the user), one of which (the UAV) can play the role of an actor for the other (the user). For the user subsystem, precedents of data loading, display with filtering and creation of mission data by the user were selected. Accordingly, an integral part of this subsystem is a user database that will store data about missions, user-provided points, tasks associated with them, and will also provide the ability to save found objects in the form of images. Because of this, special PostgreSQL data types such as dot and bytea came in handy. The dot type allows you to store an actual pair of values of any type, which in our case will be the DECIMAL(10,7) type – a number of 10 characters with 7 decimal places, which was taken from PC standards, in which geographic data has a significant part up to 7-th sign after the comma. The bytea data type allows you to store an array of bytes and is suitable for storing images, since the request to download, the image does not have to open the files name and perform read operations from the file on the server, which would significantly increase the operating time in the case of a database containing a large number found objects. As already mentioned, in the section of the analysis of ready-made solutions for a custom application, it would be possible to use a ready-made application, provided that the functionality of planning missions and displaying images in the database is available, but this was not found.

The UAV configuration environment MissionPlanner was the closest to the goals of the task, which allows you to plan missions and even perform certain manipulations

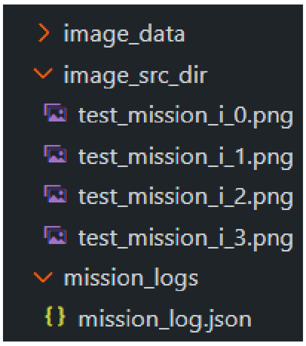

Figure 1 – The contents of the log and input image directories

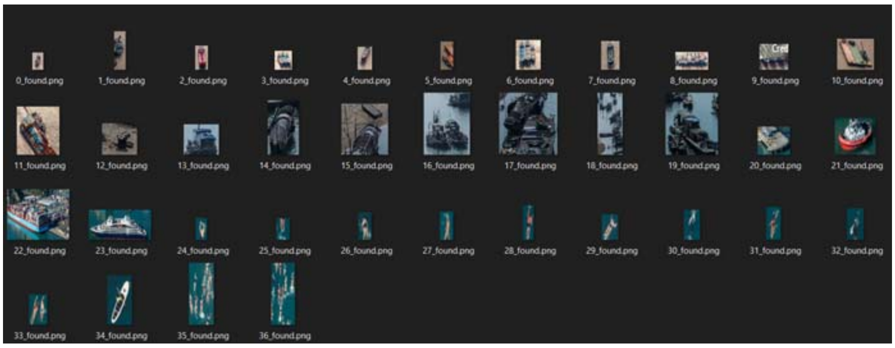

Figure 2 – Selected saved objects

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with servomotors in them, but it, like the selected flight controller, does not have functionality for working with images, as well as functionality for planning the work of NM. Accordingly, it was decided to create our own application in Python using the TKinter library.

File description:

– Overwatch_GUI.py – the main file that starts the application;

– Nav.py – a file containing a class for the application to work with geographical data, their conversion into window coordinates and vice versa;

– Frames.py – contains a description of all the windows used in the application and describes the logic of their operation;

– Db_interdace.py – a copy of a similar file from the UAV functional development section, contains a class for describing database connection management as well as predefined database interaction procedures.

Fig. 3 graphically illustrates infographic design of the information system being created, in particular, an ER diagram of the subject area is given.

This database architecture allows you to perform the design of UAV missions at the expense of the mission, waypoints tables and store the found results in the table objects found.

The custom application was designed to resemble the environment's mission planner MissionPlanner (Fig. 4).

Unfortunately, in the process of work, it was discovered that the developers of the mission planner used the TeleAtlas map from TerraMetrics (Fig. 5), which does not provide geodata for free. Because of this, it was decided to postpone the development of the map until any alternative was found. The difference between this type of map and, for example, OpenStreet map, is the satellite survey data superimposed on a coordinate grid from a three-dimensional scan of the terrain, provided to the user in response to a request for coordinates in the form of raw" data with which the user can do anything. At the same time, OpenStreet map requires integration into an existing widget, which may not provide such functionality as, for example, feedback on the coordinates of the point where the user clicked on the map.

– mission planning window;

– window for viewing observation results.

The combination of these two windows satisfies the needs of the user. Since calling a separate window for planning and displaying results would violate the user's sense of integrity, it was decided to create a user interface with a single map area and panels that would reflect the functionality of the current "window". The result was the following window forms (Fig. 6, Fig. 7).

You can see that the created planner has the same functionality as the Mission Planner, but is enhanced with a log tab where you can view grouped observations. It is worth noting that the grouping of objects occurs using the extract_clusters method from the db_interface.py file. Objects are glued into a single cluster if the distance between them is less than or equal to one-twentieth of the minimum value between the horizontal and vertical fields of view. In this case, a cluster of images is formed and the point with the found object should be displayed not in lilac, but in blue. Also, the name of the object is changed "from the one that was recorded in the database during

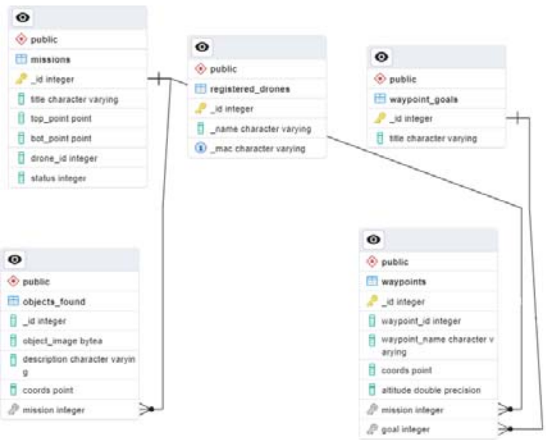

Figure 3 – ER- diagram of the subject area

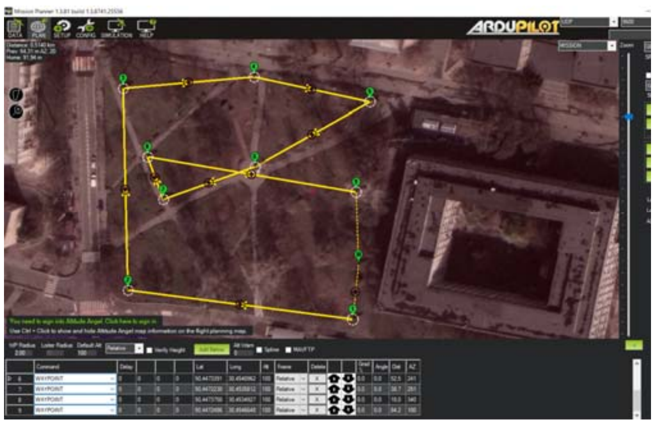

Figure 4 – Mission planner MissionPlanner

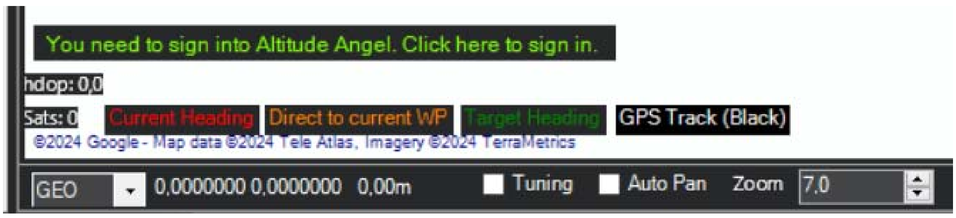

Figure 5 – Marking the map in the Mission Planner environment with data provider companies

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loading to “Object cluster #....”. The coordinate grid is less interactive and does not allow you to move with the mouse, instead a button to change the grid coordinates has been added. When you click it, the following window for changing the viewing area appears (Fig. 8).

After entering the longitude and latitude coordinates (Fig. 9), the entered data is checked and, provided that the check was successful, the coordinate grid is rescaled (Fig. 10).

When you click on a cluster, a dialog box is called in which you can see information about the objects found in this area (Fig. 11).

Based on the training results, a conclusion was made about the similarity of the training results for the two models. This gave us reason to believe that in our case the models behave equally badly and it is necessary to find a solution to this problem, either in the development process, or to provide recommendations that can improve the quality of training in the future. Because a search on the Internet led to developer notes, which stated that such situations can occur due to discrepancies between the nature of the origin of the dataset and the nature of the actual images, poor image quality, or poor image markup quality. The way out of this kind of problems can be a radical change of dataset for training. It was decided to continue development, to take into account that the system is provided with additional functionality in the form of collecting a dataset for further training, and for current use the YOLOv5 model is taken due to its smaller number of parameters and, accordingly, the need for computing power.

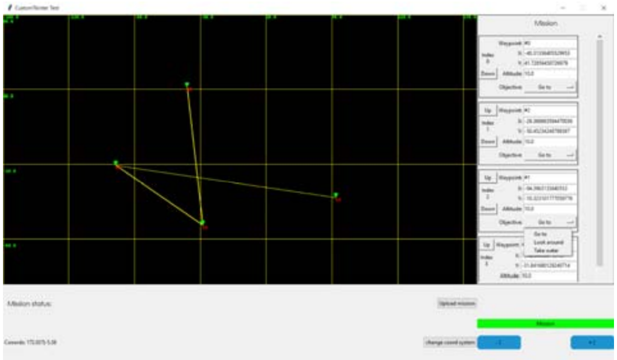

Figure 6 – Mission planning window

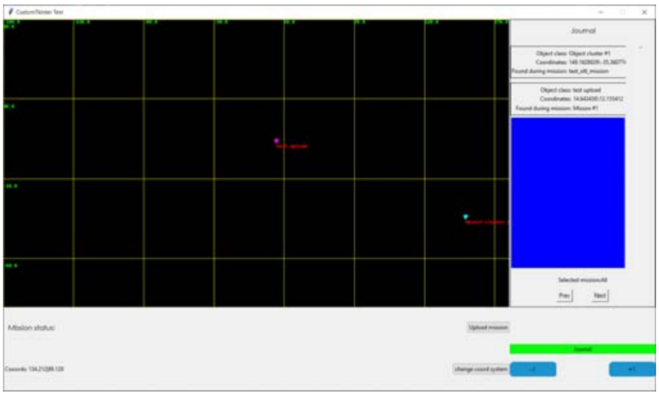

Figure 7 – Mission log window

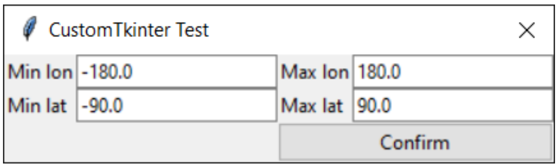

Figure 8 – Window for changing the viewing area

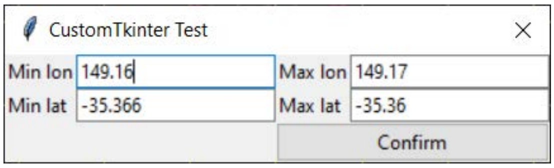

Figure 9 – New limits of the coordinate grid

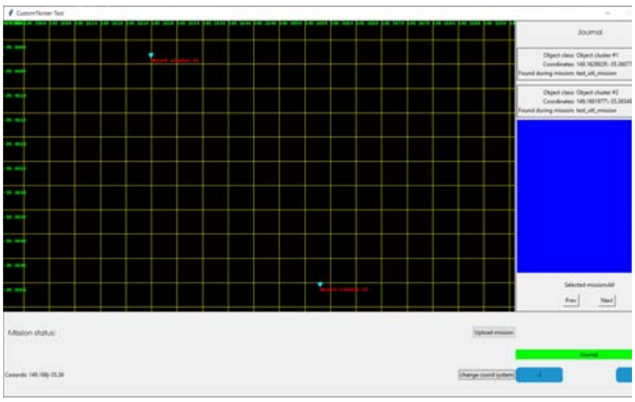

Figure 10 – Zoomed log window with redistributed clusters

Figure 11 – Dialog window for displaying information about objects

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Since the coordinates of the UAV are known, the missions (by default) are performed over a flat surface, the data related to its orientation in space, as well as the control of the tilt angle of the camera is done using a non-autonomous 2-axis gimbal. It becomes possible to solve the problem of linking the coordinates of the found object not to the place from which the shooting took place, but to the approximate location of the object itself. The algorithm for solving this problem consists of the following stages:

– Transferring coordinates from the image coordinate system to the camera's angular coordinate system, taking into account its parameters;

– Transferring the coordinates obtained in the previous stage to the coordinates of the beam, which indicates the direction from the UAV to the found object in the coordinate system related to the system of roll, yaw and pitch angles of the UAV, which will be related to such quantities as the direction to the south and an angle with the horizontal plane;

– Finding the coordinates of the point of intersection of the ray and the plane of the reservoir.

The mathematical description for the first stage is given below.

Since the neural network works with 640x640 images, it is necessary to translate these coordinates back to the coordinates of the original image:

$$A_s = A_p \cdot \begin{bmatrix} \frac{w_s}{w_p} \\ \frac{h_s}{h_p} \end{bmatrix}. \quad (1)$$

The coordinates of the original image must be normalized within the limits {–1;1} by the formula (2):

$$A_n = A_s \cdot \begin{bmatrix} \frac{2}{w_s} \\ \frac{2}{h_s} \end{bmatrix} - \begin{bmatrix} 1 \\ 1 \end{bmatrix}. \quad (2)$$

Calculation of beam angles in the camera coordinate system is carried out as follows. Considering that the camera manufacturer specified the angle of its field of view as the length in degrees of the captured image diagonal, it is possible to translate the image coordinates into the beam coordinates as follows:

$$FOV = F_x^2 + F_y^2 . \quad (3)$$

$$\frac{F_x}{F_y} = \frac{w_s}{h_s} \to F_y = \sqrt{\frac{FOV}{(\frac{w_s^2}{h_s^2}+1)}} . \quad (4)$$

$$F_x = F_y \cdot \frac{w_s}{h_s}$$

The coordinates are as:

$$A_w = A_n \cdot 0.5 \cdot \begin{bmatrix} F_x \\ F_y \end{bmatrix}. \quad (5)$$

Mathematical description for the second stage:

The transfer to the UAV coordinate system occurs as a sequential transfer of the angle (see the first stage of the mathematical description) to *P*, *R* and *Y* angles.

$$A_r = (A_w + \begin{bmatrix} P \\ R \end{bmatrix}) \bullet \begin{bmatrix} \cos(Y) & -\sin(Y) \\ \sin(Y) & \cos(Y) \end{bmatrix}. \quad (6)$$

Mathematical description for the third stage:

Calculation of displacement in meters in the UAV coordinate system with reference to Alt looks like this

$$s = Alt \cdot \mathrm{tg}(A_{r1}) . \quad (7)$$

Translation of the shift (see stage 2 of the mathematical description) into a shift in geodetic coordinates with reference to the location of the UAV (*N*, *E*, *Alt* :

$$A` = s \cdot \begin{bmatrix} tg(A_{r0}) \\ tg(A_{r0}) \end{bmatrix} \circ \begin{bmatrix} \frac{1}{lat1} \\ \frac{1}{lon1} \end{bmatrix} = s \cdot \begin{bmatrix} \cos(A_{r0}) \\ \cos(A_{r0}) \end{bmatrix} \circ \begin{bmatrix} \frac{1}{111134.861} \\ \frac{1}{111319.444 \cdot \cos(N)} \end{bmatrix}. \quad (8)$$

The proposed mathematical description, which calculates the coordinates of the object based on the dimensions of the original image from the camera, the dimensions of the image with which the neural network works, the angle of the field of view of the camera, the position of the UAV and the angles of roll, pitch and yaw, allows you to transfer the coordinates of the object found by the NN, in the image to geographic coordinates, thereby moving away from the rigid reference to UAV coordinates.

4 EXPERIMENTS

The computer program implementing the proposed method, which complements mission planning, recognition of found objects using neural network technologies, and the process of creating a mission log for subsequent processing.

The simulation places the UAV by default on the coast of Australia, so it was decided to demonstrate a test flight in this area (Fig. 12).

The approximate starting point of the mission is given on Fig. 13.

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Setting the coordinate grid of the planner for a given area is shown on Fig. 14.

The mission route in the written mission planning environment is shown in Fig. 15. The current image of the mission contains a display of the mission trajectory on the map and a list with the possibility of editing the coordinates of reference points. It is possible to enter and edit the name of the mission when opening it for uploading to the database.

The request to display the newly saved data in the database has the form shown in Fig. 16. In Fig. 16, a) shows a table characterizing the missions, and Fig. 16, b) the table of reference points of the mission is displayed.

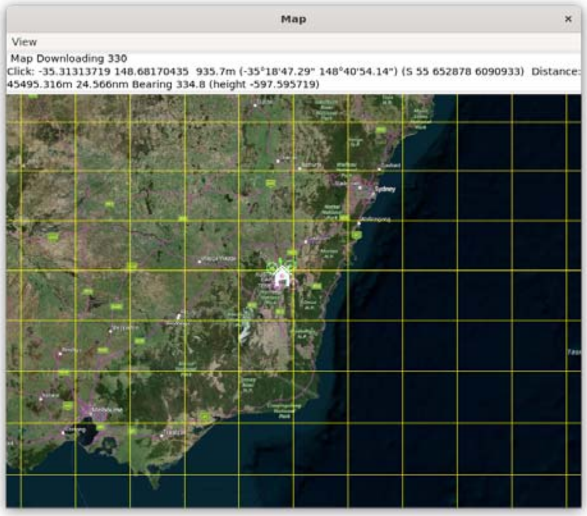


Figure 12 – The starting point of the simulation

Figure 13 – Mission start point (approximate)

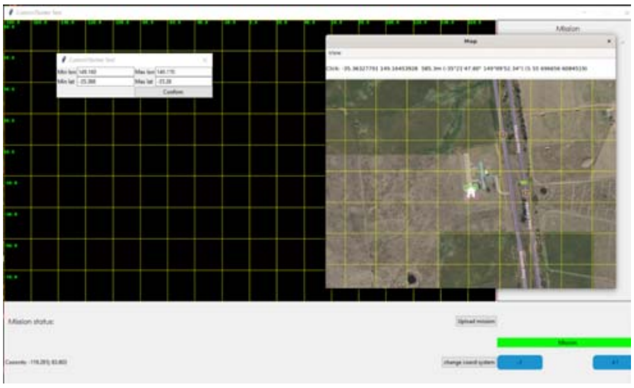


Figure 14 – Setting the coordinate grid of the planner for a given area

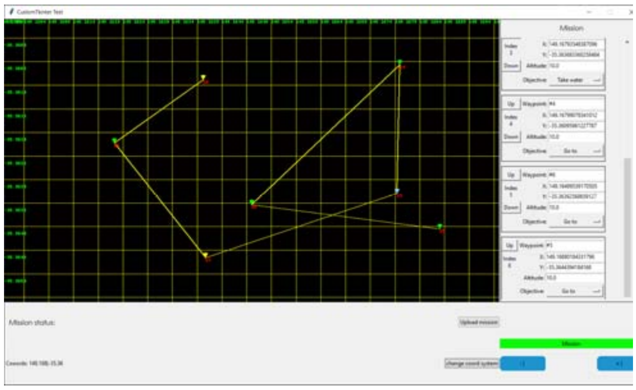
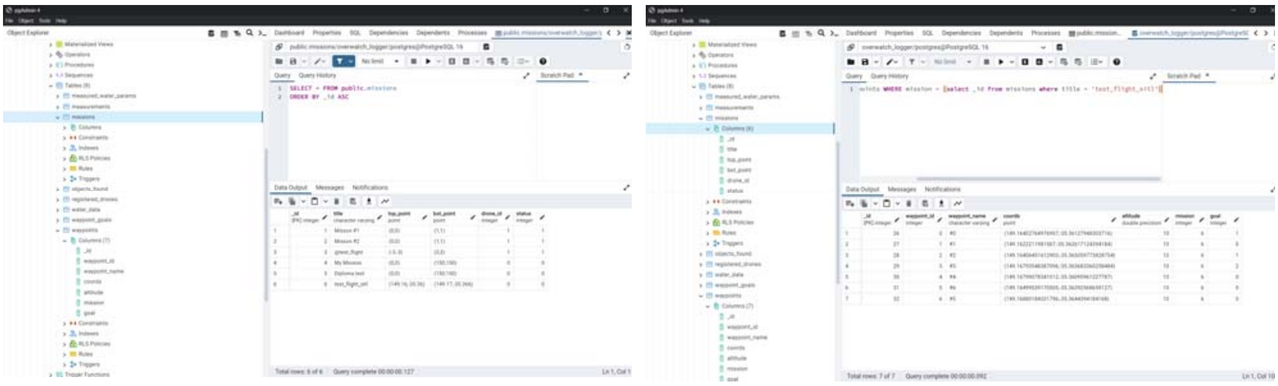


Figure 15 – A mission route in a written mission planning environment



a b

Figure 16 – Request to display newly saved data in the database:
a – table characterizing the missions; b – table of reference points of the mission

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In the future, it is necessary to launch the UAV system. In Fig. 17 shows the movement of the UAV along the reference points of the mission, the special designations for the initial and next points and the conventional designations of the UAV rotors are illustrated. The results of observations downloaded from the logbook into the database are shown in Fig. 18.

5 RESULTS

Accordingly, the new images from the database, which were displayed in the graphical user interface, have the form shown in Fig. 19. Fig. 19, a has a greater degree of distance, and Fig. 19, b illustrates the process of revealing clusters of images when zooming in.

We can see 2 clusters corresponding to the position of the view points that were described in the mission description. The images in the clusters correspond to the test images.

The images in the upper cluster are shown in Fig. 20. These include group (Fig. 20, a) and individual (Fig. 20, b) images. A more detailed study of object detection accuracy and methods of increasing it are described in the work of the authors [20].

In this way, the functionality of the system was tested, the generation and saving of the logbook was tested, the features of information presentation in the logbook were considered, the effectiveness of the interaction of the components of the created information system was evaluated, the operation of the proposed hardware and software complex for the study of water bodies was analyzed using the SITL environment from the flight controller developers.

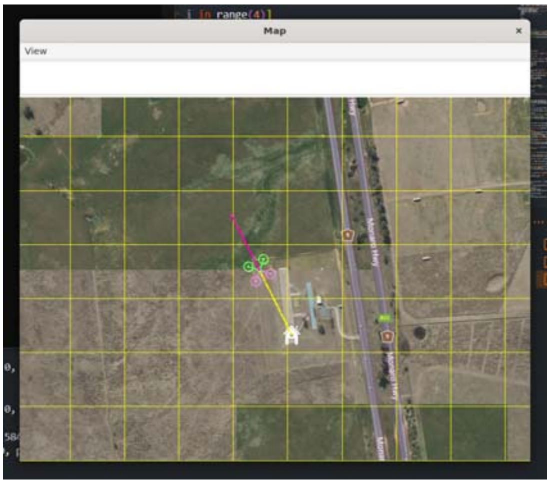


Figure 17 – Movement of the UAV along mission reference points

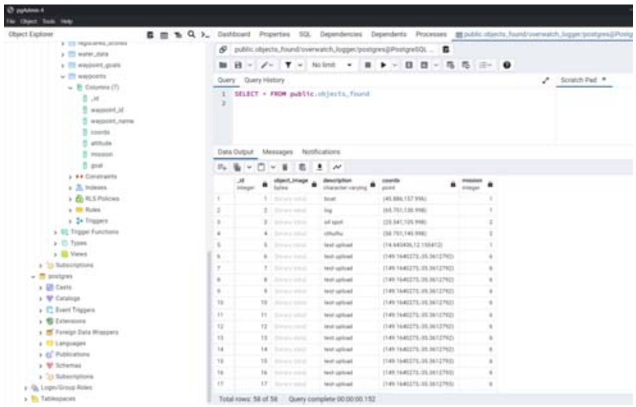
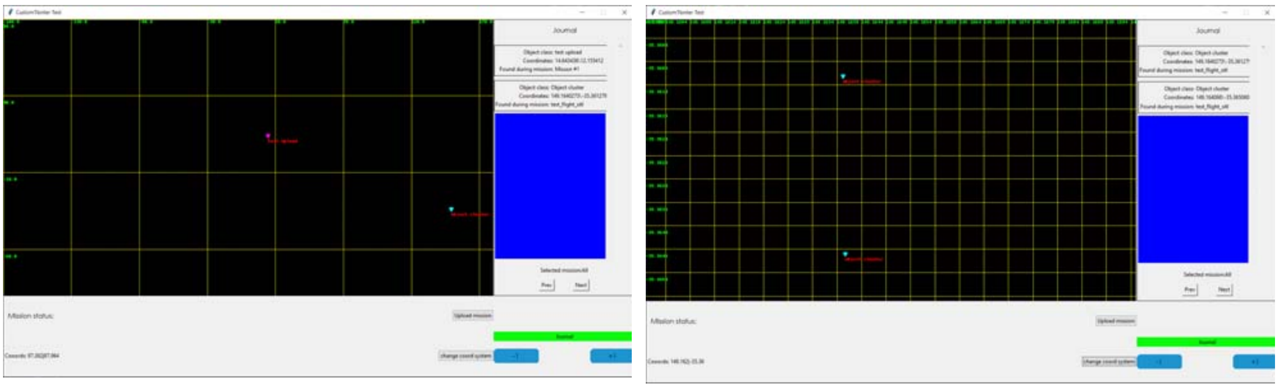


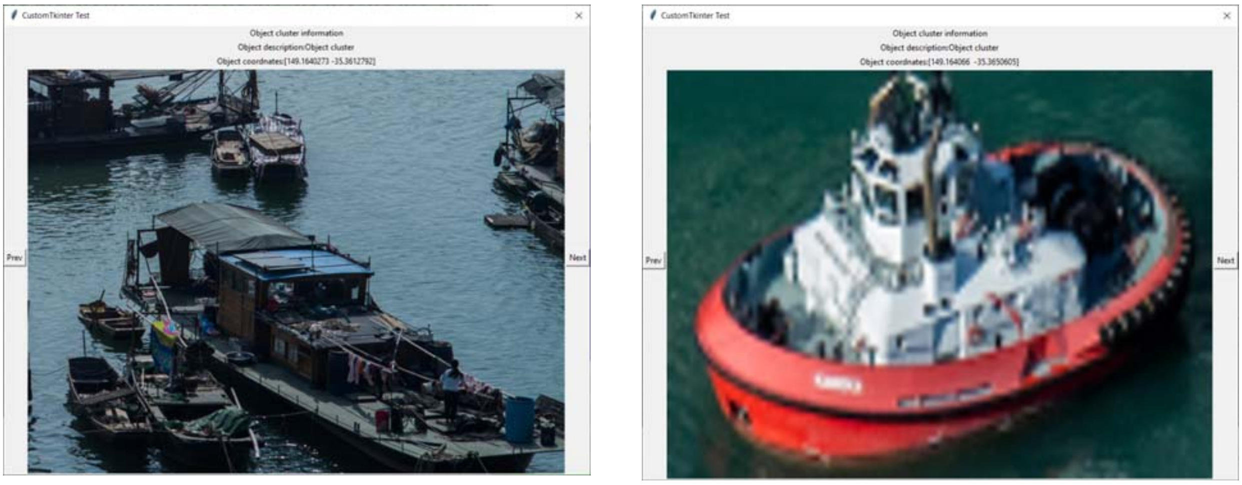
Figure 18 – The results of observations downloaded to the database from the logbook



a b

Figure 19 – New images from the database that were displayed in the graphical interface
a – has a greater degree of remoteness; b – illustrates the process of revealing clusters of images when zooming in

DOI 10.15588/1607-3274-2024-3-9



a b

Figure 20 – Examples of images received by the user from UAVs
a – group images; b – single images

6 DISCUSSION

In the process of developing the system, a problem arose: due to the reduction of the accuracy threshold for NM, it began to recognize one object as different objects of different classes. In order to avoid this phenomenon, which would lead to the overflow of the UAV's local storage with a large number of photos of the same object, it was decided to add a stage of post-processing of the predictions of the neural network, which will be based on an algorithm similar to the filtering algorithm already implemented in the neural network, which suppresses re-detection of the object by the network and is based on the area of intersection of the detected rectangles. In this way, it was possible to propose a mechanism for creating a flight log and implement a hardware and software complex of an information system for uploading information about the mission to the database by certain means and further work with this data regarding the classification and recognition of relevant objects.

CONCLUSIONS

The problem of systematization of objects detected during the mission on the surface of water bodies was solved by creating a flight log, organizing interaction with a neural network, applying post-processing of recognized objects, mathematically transforming the coordinates of objects for display and visualization into geographic coordinates, thereby moving away from rigid binding to UAV coordinates.

The scientific novelty of obtained results is that the proposed mathematical description, which calculates the coordinates of the object, based on the dimensions of the original image from the camera. The dimensions of the image with which the neural network works, the angle of the camera's field of view, the position of the UAV and the angles of roll, pitch and yaw, allow you to transfer the coordinates of the object found by the NM in the image to geographic coordinates, thereby moving away from the rigid reference to the coordinates of the UAV.

The practical significance of obtained results is that a workable logbook generation and storage system has been created, which takes into account the peculiarities of information presentation in the logbook, and ensures effective interaction of the components of the created information system within the proposed hardware and software complex, which allows organizing the process of researching water bodies according to using the SITL environment from the flight controller developers.

Prospects for further research are to study the proposed set of indicators for a broad class of practical problems. Prospects for further research should include the need to implement and test the developed hardware and software complex for collecting statistical data on the recognition and classification of objects for a specific field of application with a certain nomenclature of objects.

ACKNOWLEDGEMENTS

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БОРТОВИЙ ЖУРНАЛ ТА ПЕРЕТВОРЕННЯ КООРДИНАТ ДЛЯ ДЕТЕКЦІЇ ОБ’ЄКТІВ НА ПОВЕРХНІ ВОДОЙМ

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АНОТАЦІЯ

Актуальність роботи обумовлена попитом на технології БПЛА з інтеграцією штучного інтелекту в умовах сьогодення.

Мета роботи – розробити мінімальну робочу версію БПЛА-дослідника та програмного забезпечення для керування даним БПЛА.

Метод. Запропоноване математичне описання, яке вираховує координати об’єкту, спираючись на розміри оригінального зображення від камери, розміри зображення з яким працює нейромережа, кут поля зору камери, положення БПЛА та кути крену, тангажу та рискання, дозволяє перенести координати об’єкту, знайденого НМ, на зображенні у географічні координати, тим самим відійти від жорсткої прив’язки до координат БПЛА.

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Результати. Було вирішено проблему систематизації детектованих в ході місії об'єктів на поверхні водойм шляхом формування журналу польоту, організації взаємодії з нейромережею, застосування пост обробки розпізнаваних об'єктів, математичного перетворення координат об'єктів для відображення і візуалізації у географічних координати, тим самим відійти від жорсткої прив'язки до координат БПЛА.

Висновки. Створено працездатну систему генерації та збереження бортового журналу, яка враховує особливості представлення інформації в бортовому журналі, та забезпечує ефективну взаємодію компонентів створеної інформаційної системи у межах запропонованого апаратно-програмного комплексу, що дозволяє організувати процес дослідження водойм за допомогою середовища SITL від розробників польотного контролеру.

КЛЮЧОВІ СЛОВА: БПЛА, польотний контролер, журнал місії, нейронна мережа, географічні координати, розпізнані зображення, точність прогнозу, постобробка зображень.

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ІНТЕЛЕКТУАЛЬНА ПІДТРИМКА ПРОЦЕСІВ ПОШУКУ ТА ВИЛУЧЕННЯ ПРЕЦЕДЕНТІВ У CBR-ПІДХОДІ

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АНОТАЦІЯ

Актуальність. Ситуаційний підхід ґрунтується на використанні моделей та методів прийняття рішень у реальному часі у міру виникнення проблем відповідно до поточної ситуації. Ефективним інструментом реалізації концепцій ситуаційного підходу є метод міркувань за прецедентами. Міркування на основі прецедентів дозволяє вирішувати нові проблеми, використовуючи знання про минулі проблеми та накопичений досвід їх вирішення. Оскільки прототипи (прецеденти), що описують сценарій вирішення певної проблемної ситуації, зберігаються у бібліотеці прецедентів, їх пошук та вилучення безпосередньо визначають час відгуку системи. В цих умовах виникає необхідність пошуку шляхів вирішення актуальної науково-практичної проблеми спрямованої на оптимізацію процесу пошуку та вилучення прецедентів. Об'єктом дослідження є процеси подання та вилучення прецедентів із бібліотеки прецедентів.

Метою роботи є удосконалення процедури пошуку в *CBR*-підході за рахунок звуження допустимої для вирішення поточної цільової ситуації множини прецедентів, та виключення із подальшого аналізу таких прецедентів, що не відповідають заданому переліку параметрів поточної ситуації.

Метод. Методика дослідження ґрунтується на застосуванні методів теорії грубих множин для вдосконалення процедури пошуку рішень на основі міркувань за прецедентами, що покладена в основу *CBR*-підходу. Запропонована в роботі двоетапна процедура звуження вихідної множини прецедентів передбачає попередню фільтрацію прецедентів, значення параметрів яких належать заданим околицям відповідних параметрів цільової ситуації на першому етапі, та додаткове звуження отриманої підмножини прецедентів методами теорії грубих множин на другому етапі. Визначення *R*-нижньої та *R*-верхньої апроксимацій заданої цільової множини прецедентів у рамках нотації теорії грубих множин дозволяє розділяти (сегментувати) вихідну, доступну для вирішення поточної проблеми множину прецедентів на три підгрупи (сегменти). Пошук прототипів рішень може бути здійснено серед виділеної підмножини прецедентів, які із точністю можуть бути класифіковані як такі, що належать заданій цільовій множині; які з деякою часткою ймовірності можуть бути віднесені до заданої цільової множини, або в рамках об'єднання цих двох підмножин. Третя підмножина містить прецеденти, які безумовно не належать заданій цільовій множині і можуть бути виключені із подальшого розгляду.

Результати. Розглянуті питання подання та виведення знань на основі прецедентів. Вдосконалено процедуру пошуку прецедентів в БПр з метою зменшення часу відгуку системи, необхідного на пошук найбільш близького до поточної ситуації рішення, за рахунок звуження вихідної множини прецедентів для подальшого пошуку.

Висновки. Дістав подальшого розвитку метод міркувань за прецедентами на основі математичного апарату теорії грубих множин. Запропонований підхід, на відміну від класичного *CBR*-підходу, дозволяє моделювати невизначеність щодо приналежності / неприналежності прецеденту заданій цільовій множині, вилучати із подальшого розгляду прецеденти, що їй не відповідають.

КЛЮЧОВІ СЛОВА: теорія грубих множин, метод міркувань за прецедентами, бібліотека прецедентів, цільова множина, апроксимація цільової множини.

АБРЕВІАТУРИ

БЗн – база знань;
БПр – бібліотека прецедентів;
ІС – інформаційна система;
ОПР – особа, яка приймає рішення;
ПрО – предметна область;
СЗн – система знань;
ТГМ – теорія грубих множин;
CBR – Case-Based Reasoning.

НОМЕНКЛАТУРА

$BN_R(X)$ – гранична область множини X;
C –множина концептів ПрО, яку визначає онтологія O;
$Case_{targ}$ – цільовий прецедент;
$Case_i$ – прецедент БПр;
CL – бібліотека прецедентів;
E_h– клас еквівалентності;
F – множина функцій інтерпретації, заданих на концептах та / або відношеннях онтології O;
$IND(R)$ – класи еквівалентності (категорії) елементів універсума, які сформовані на основі R;
$NEG_R(X)$ – негативна область множини X;
P – множина параметрів поточної ситуації s;
$POS_R(X)$ – позитивна область множини X;
R – відношення еквівалентності;
Rel – скінчена множина відношень між концептами (поняттями) ПрО;
$\overline{R}X$ – верхня R-апроксимація множини X;
$\underline{R}X$ – нижня R-апроксимація множини X;
S – множина всіх можливих ситуацій, що належать аналізованій ПрО;
U – універсум об'єктів, що розглядаються;

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U / R – сімейство всіх класів еквівалентності (класифікацій універсума);

$U_{targ.}$ – цільова множина;

$[x]_R$ – категорія в R, що містить елемент $x \in U$;

V_{p_l} – множина значень параметру $p_l \in P$;

W – множина вагових коефіцієнтів $w_l \in W$ відповідних параметрів $p_l \in P$;

d – рішення, що пропонується для розв'язання ситуації s;

m – кількість параметрів цільової ситуації s;

$\min_l$ – мінімально можливе значення параметру $p_l \in P$;

$\max_l$ – максимально можливе значення параметру $p_l \in P$;

r – результат застосування рішення d;

s – ситуація, що описує прецедент *Case*;

$| H |$ – кардинальність множини H.

ВСТУП

Посилення динамічності та мінливості чинників зовнішнього середовища, підвищення інтенсивності конкуренції особливо в умовах поглибленням кризових явищ в економіці, зростання складності завдань, що вирішуються в умовах невизначеності та ризику, безпосередньо пов'язано із щоденним вирішенням взаємоузгоджених та взаємопов'язаних задач, що виникають у складних організаційних, технічних, соціальних, економічних та інших системах. В таких умовах вирішення проблеми пошуку оптимальних шляхів досягнення тактичних та стратегічних цілей поступово зумовлює відмову від класичних принципів менеджменту, представленого «програмно-цільовим управлінням» і перехід до застосування більш гнучких та ефективних принципів та методів ситуаційного підходу, в основу якого покладена командна робота, побудована на взаєморозумінні та консенсусі осіб, які приймають рішення, особливо в умовах реального часу.

Вибір та прийняття ефективних рішень значно ускладнюється в умовах багатокритеріальності, збільшенні числа альтернативних варіантів рішення, насамперед при вирішенні слабоструктурованих (змішаних) та неструктурованих задач, які характеризуються наявністю частково формалізованих або неформалізованих якісних факторів, особливо якщо спостерігається тенденція до збільшення їх кількості. В цих умовах ОПР не може на евристичному рівні приймати ефективні рішення приймаючи до уваги сукупність факторів які впливають на досягнення поставленої цілі.

Концепція ситуаційного підходу заперечує формальне слідування створеним раніше правилам вирішення проблемної ситуації без належного аналізу її суті, та базується на детальному аналізі всіх особливостей поточної проблемної ситуації, використовуючи накопичений досвід для її вирішення та оцінку можливих негативних наслідків [1]. Ситуаційних підхід спирається на суб'єктивні і евристичні знання фахівців (команду спеціалістів з ПрО) і полягає в прийнятті рішень по мірі виникнення проблем відповідно до поточної ситуації.

В якості «інструментів» реалізації ситуаційного підходу використовуються інтелектуальні системи підтримки прийняття рішень, невід'ємною частиною яких є БЗн. В основі створення БЗн знаходиться модель знань про ПрО ситуацій, за якими потрібно оперативно приймати рішення.

Основні положення та принципи ситуаційного підходу отримали подальший розвиток в методі міркувань на основі прецедентів [2–4]. Цей метод з'явився внаслідок того, що велика кількість практичних задач є погано формалізованими, причому невизначеність не має ймовірнісний характер. При пошуку рішень подібних задач необхідно застосовувати методи правдоподібного виведення, що дозволяють знайти прийнятне (краще із можливих, але необов'язково оптимальне) рішення.

Застосування підходу до виведення рішень на основі міркувань за прецедентами основане на ідеї використання накопиченого досвіду для вирішення нових проблем на основі вже існуючих рішень (прецедентів). Людина (експерт, аналітик, ОПР) на етапі пошуку рішень нової (невідомої) задачі намагається використовувати рішення, які приймались раніше в подібних ситуаціях, і при необхідності адаптувати їх до поточної проблеми.

Об'єктом дослідження є процеси подання та вилучення прецедентів із БПр.

Предметом дослідження є моделі та методи подання та виведення знань ПрО.

Метою роботи є удосконалення процедури пошуку в *CBR*-підході за рахунок звуження допустимої для вирішення поточної цільової ситуації множини прецедентів, та виключення із подальшого аналізу таких прецедентів, що не відповідають заданому переліку параметрів поточної ситуації.

1 ПОСТАНОВКА ЗАДАЧІ

Припустимо, що в деякий момент часу t виникає певна ситуація $s(t) \in S$, що потребує вирішення. На основі аналізу поточної ситуації ОПР формулює мету $g_{s(t)}$, досягнення якої, на його думку, дозволить вирішити проблемну ситуацію $s(t)$; визначає які засоби є допустимими для її досягнення; аналізує фактори, що впливають на її вирішення; прогнозує можливі наслідки ухвалення того чи іншого рішення; ухвалює певне рішення $d_{s(t)}$, що приводить до досягнення поставленої мети $g_{s(t)}$ і вирішення ситуації $s(t)$; оцінює його якість та ефективність. Для досягнення цілі $g_{s(t)}$ може бути запропоновано декілька альтернативних варіантів рішень $D = \{d^j_{s(t)} \mid j = \overline{1,k}\}$, обране рішення $d_{s(t)} \in D$, може не бути оптимальним, але воно є найкращим серед можливих, враховуючи встановлені цілі, накладені умови та обмеження.

Таким, чином опис проблемної ситуації та шляхів її вирішення може бути подано у формі прецеденту

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$Case_{s(t)} = \langle s(t),\ d_{s(t)} \rangle$. Відповідно, множина всіх вирішуваних в рамках модельованої ПрО проблемних ситуацій та прийнятих для їх вирішення рішень, утворюють БПр системи $CL = \{Case^{i}_{s(t)} \mid i = \overline{1,|S|}\}$.

Як правило, процес виведення на основі прецедентів складається із чотирьох основних кроків, що утворюють так званий цикл міркувань на основі прецедентів або *CBR*-цикл [5], основними етапами якого є:

– вилучення (*retrieve*) найбільш подібного прецеденту (або прецедентів) для поточної ситуації із БПр;

– адаптація або повторне використання (*adapt or reuse*) вилученого прецеденту для спроби рішення поточної проблеми;

– перегляд або оцінка (*evaluate or revise*), за необхідністю, отриманого рішення у відповідності до поточної проблеми;

– дослідження або збереження (*learn or retain*) прийнятого рішення як частини нового прецеденту.

Перший етап є найбільш трудомістким, особливо якщо спостерігається тенденція до збільшення кількості параметрів, що описують аналізовану ситуацію $s(t)$.

Задача полягає в пошуку такого прецеденту $Case^{i}_{s(t)} \in CL$, який є найбільш близьким до цільового прецеденту $Case_{s(t)}$, що описує аналізовану ситуацію $s(t)$ за найменший можливий час, що є особливо актуальним питанням при розв'язанні задач в режимі реального часу.

Задача значно ускладнюється, за умови, що не всі параметри, які описують поточну ситуацію задані (існують пропущені значення параметрів), наприклад, у випадку відсутності актуальної, достовірної, об'єктивної інформації.

2 ОГЛЯД ЛІТЕРАТУРИ

Метод міркувань на основі прецедентів активно застосовується в системах експертного діагностування [6], системах підтримки прийняття рішень [7–8], системах машинного навчання, при вирішенні задач прогнозування, узагальнення накопиченого досвіду, пошуку рішень в маловивчених ПрО [9–10].

До переваг *CBR*-методу слід віднести відносну легкість процесу набуття експертних знань; метод передбачає механізми вирішення важко формалізованих проблем (слабо структурованих та неструктурованих задач) в певній ПрО; врахування минулого досвіду (вдалих рішень) при вирішенні нової проблеми шляхом адаптації найбільш близького до поточної ситуації прецеденту; пояснення отриманого рішення за рахунок аналізу успішних найбільш близьких прецедентів [4]. В той же час метод не є прийнятним для вирішення принципово нових (унікальних) задач, при розв'язані яких відсутній минулий (накопичений) досвід (не підтримується вимога регулярності, або повторюваності задач певного типу); зі збільшенням кількості параметрів ситуації, яку описує прецедент, зростає складність процесів пошуку подібних випадків та адаптація існуючих прецедентів.

При використанні виведення на основі прецедентів виникають дві ключові задачі: пошук найбільш відповідних прецедентів і подальша адаптація знайденого рішення. В основі всіх підходів до пошуку та вилучення прецедентів з БПр лежить той чи інший спосіб вимірювання ступеня близькості між прецедентом і поточною проблемною ситуацією. Для вирішення цієї задачі запропоновано низку підходів, таких як метод «найближчого сусіда», штучні нейронні мережі, метод Байєса, метод дерев рішень, методи теорії нечітких множин та ін. [4]. Перелічені підходи, незважаючи на їх переваги, мають ряд недоліків, серед яких можна виділити наступні: необхідність використання (збір та попередня підготовка) додаткової інформації при реалізації того чи іншого методу; відсутність обґрунтованого уніфікованого підходу до вибору міри близькості; суб'єктивність вибору вагових коефіцієнтів важливості параметрів прецеденту (здебільшого призначаються експертним шляхом); низька ефективність при обробці засмічених даних, даних із пропущеними значеннями, та ін. Серед вищезазначених методів найбільшого поширення набув метод «найближчого сусіда». Його привабливість полягає у простоті реалізації, стійкості до викидів (аномальних даних) та відсутності необхідності навчання моделі; в той же час слід відмітити, що цей алгоритм використовує схему повного перебору кейсів БПр, що суттєво знижує його ефективність, особливо для великих БПр. Проблема ефективності пошуку прецедентів може бути вирішена шляхом індексації БПр [11–14], яка дозволяє суттєво зменшити час пошук рішення. Важливим питання в процедурі індексації БПр є вибір методу індексування, якщо обрана схема індексування є не задовільною, то найближчі до цільової ситуації прецеденти можуть бути відсічені в процесі пошуку рішення, і, як наслідок, виникатиме проблема адаптації менш близьких до поточної ситуації прецедентів.

Задача адаптації та використання знайденого рішення є недостатньо формалізованою і сильно залежить від ПрО. Проблема адаптації рішень виникає в ситуаціях, коли в процесі вирішення поточної проблеми *CBR*-система в БПр не знаходить досить близького до поточної ситуації прецеденту і, як наслідок, не може рекомендувати готового рішення, у цьому випадку виникає задача модифікації наявного рішення для застосування в поточній ситуації. У [4] виділено два основні підходи, спрямовані на адаптацію наявного рішення. Традиційний підхід передбачає залучення експертів з відповідної ПрО для адаптації отриманого рішення до поточної ситуації. Вилучені експертні знання можуть бути представлені у форматі таблиць, семантичних дерев, продукційних правил «ЯКЩО-ТО» [15–17]. Такий підхід до набуття знань про адаптацію є трудомістким і потребує багато часу. Альтернативний варіант припускає, що знання з адаптації конкретної задачі можна отримати з кейсів (пре-

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цедентів) на основі методів машинного навчання (нечітких дерев рішень, штучних нейронних мереж, байєсівських моделей, генетичних алгоритмів, та ін.) [19–21]. Методами машинного навчання генеруються спеціалізовані евристики, які пов'язують відмінності у вхідних специфікаціях (параметрах-атрибутах проблеми) з відмінностями у вихідних специфікаціях (параметрах-атрибутах рішення). Ці евристики можна використовувати для визначення відповідного ступеня адаптації. Перевага таких методів полягає в тому, що знання про адаптацію можна отримати автоматично (вони є більш надійними та менш суб'єктивними).

3 МАТЕРІАЛИ І МЕТОДИ

У загальному вигляді модель прецеденту може бути подана кортежем виду [4]:

$$Case=<s, d, r>. \quad (1)$$

В якості ситуації *s*, що описує прецедент можна розглянути, наприклад, сукупність симптомів хворого із загальним патогенезом, тоді рішенням *d* є діагноз захворювання і рекомендації ОПР.

Для опису поточної ситуації використовують параметричну модель у вигляді набору параметрів з конкретними значеннями:

$$s = (P, V, W). \quad (2)$$

В моделі (2) перший параметр $P = \{p_l \mid l = \overline{1,m}\}$ являє собою не порожню скінчену множину параметрів поточної ситуації; $V = \bigcup_{p_l \in P} V_{p_l}$, V_{p_l} – множина значень параметру p_l; $W = \{w_l \mid l = \overline{1,m}\}$ – множина вагових коефіцієнтів відповідних параметрів (w_l вага параметру p_l).

Параметри поточної ситуації можуть містити набір характеристичних ознак, що однозначно описують аналізовану ситуацію, поставлені цілі та обмеження, що накладаються специфікою вирішуваної задачі.

Однак, в ряді випадків при параметричному представленні важко враховувати залежність між параметрами прецеденту (наприклад, причинно-наслідкові залежності). Одним із способів вирішення такої проблеми є подання прецедентів на основі методології онтологій ПрО.

Під формальною моделлю онтології (*O*) розуміють впорядковану трійку (кортеж) виду [21]:

$$O = <C, Rel, F>. \quad (3)$$

Таким чином, онтології на базовому рівні повинні, перш за все, забезпечувати словник понять (термінів) для подання та обміну знаннями про ПрО і множину зв'язків (відношень), встановлених між поняттями цього словника. Для формалізованого подання онтологій широкого застосування набули продукційні моделі, семантичні мережі, фрейми, та ін. [21]. Це дає можливість формування гібридних моделей подання прецедентів. Таким чином, параметрична модель подання прецедентів виду (2), може бути розширена елементами продукційної моделі за допомогою експертних правил продукційного типу («ЯКЩО» *умова*, «ТО» *дія*), на основі яких можна описати і встановити залежності між параметрами прецедентів і проблемної ситуації для конкретної ПрО, а також отримати висновки щодо невідомих фактів (наприклад, встановити відсутні значення деяких параметрів при описі поточної ситуації і т.п.). Для подання існуючої СЗн в більш наглядній та структурованій формі, модель виду (1) можна розширити, використовуючи для цього семантичні мережі. В семантичній мережі структура знань про ПрО формалізується у вигляді орієнтованого графа з позначеними вершинами і дугами, що дає можливість описати різні відношення між параметрами прецедентів.

Разом з тим, достатньо часто в реальних ситуаціях доводиться вирішувати задачі вилучення знань з масивів невпорядкованих даних, що викликає певні труднощі. Методи ТГМ дозволяють обробляти імпліцитні (неявні) масиви невпорядкованих даних і на цій основі отримувати нові знання [22–24].

ТГМ розглядається, як концепція і теоретична основа міркувань про знання, коли вони неточні (невпорядковані). Фактично знання в ТГМ складаються з сімейства різноманітних зразків класифікації аналізованої ПрО.

Припустимо $U \neq \varnothing$ скінчена множина (універсум) об'єктів, що розглядаються. Будь-яка підмножина $X \subseteq U$ універсуму є категорією в U, та будь-яке сімейство категорій в U вважається знаннями та утворюють існуючу СЗн.

ТГМ базується на категоріях, які формують розбиття (класифікацію) певного універсуму *U*, тобто на отриманні такого сімейства $Y = \{X_1, X_2, \ldots, X_n\}$, що $X_i \subseteq U$, $X_i \neq \varnothing$, $X_i \cap X_j = \varnothing$ для $i \neq j$, $(i, j = 1,\ldots,n)$ та $\cup X_i = U$. Множина основних аспектів класифікації *Y* (наприклад, вік, форма, відтінки кольору та ін..) отримала назву БЗн на U.

Таким чином існуюча СЗн може бути подана у формі БЗн $K=(U, R)$. На основі *R* в ТГМ проводиться процедура класифікації об'єктів універсуму, яка є більш простою, ніж відомі вирішуючі правила. На основі *R* можуть бути сформовані класи еквівалентності (категорії) елементів. Кожна така категорія містить елементи універсуму, що мають спільні властивості (атрибути), всередині кожної такої категорії елементи вважаються нерозрізненими.

ТГМ дозволяє моделювати невизначеність щодо приналежності елементів універсуму заданій цільовій множині $X \subseteq U$, та отримувати її кількісну оцінку на основі обрахунку нижньої та верхньої апроксимацій цієї множини [22–23].

Відповідно до нотації ТГМ будь який елемент універсуму $x \in U$ може належати: нижній *R*-апроксимації

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заданої множини X ($x \in \underline{R}X$); верхній R-апроксимації заданої множини X ($x \in \overline{R}X$); не належати множині X ($x \notin X$), якщо елемент належить до її негативної області ($x \in NEG_R(X)$).

На відміну від ТГМ, теорія множин підтримує однозначну приналежність елемента до заданої множини; теорія нечітких множин вводить поняття функції приналежності $\mu_X(x)$, $x \in X$, $\mu_X(x) \in [0; 1]$, яка виражає суб'єктивний ступінь впевненості в тому, що $x \in X$.

$\underline{R}$ -нижньою апроксимацією грубої множини X вважається така підмножина елементів U, які із упевненістю належать до цільової множини X:

$$\underline{R}X = \{x \in U : [x]_R \subseteq X\}, \text{ або } x \in \underline{R}X, \text{ тоді і тільки тоді, коли } [x]_R \subseteq X. \quad (4)$$

$\overline{R}$ -верхньою апроксимацією грубої множини X вважається така підмножина елементів U, які можуть належати до цільової множини X:

$$\overline{R}X = \{x \in U : [x]_R \cap X \neq \varnothing\}, \text{ або } x \in \overline{R}X, \text{ тоді і тільки тоді, коли } [x]_R \cap X \neq \varnothing. \quad (5)$$

Іншим способом визначення грубої множини є ведення грубої функції приналежності [25], $\mu_X^R(x) \in [0;1]$:

$$\mu_X^R(x) = \frac{|X \cap R(x)|}{|R(x)|}. \quad (6)$$

Функція (6) дозволяє кількісно оцінити ступінь перекриття множини X та класу еквівалентності $R(x)$, до якого належить x, та виражає ступінь приналежності $x \in U$ до множини X, беручи до уваги інформацію, що надає R, рис. 1.

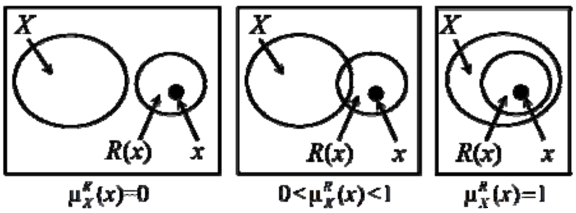

Рисунок 1 – Графічне подання грубої функції приналежності

Груба функція приналежності є узагальненням нечіткої функції приналежності; функція (6) має ймовірнісну природу та не може бути визначена для перетину та об'єднання заданих множин [26].

$\underline{R}$ -нижня та $\overline{R}$ -верхня апроксимації грубої множини X також можуть бути виражені через функцію (6):

$$\underline{R}X = \{x \in U : \mu_X^R(x) = 1\}. \quad (7)$$

$$\overline{R}X = \{x \in U : \mu_X^R(x) > 1\} \quad (8)$$

R-позитивна область цільової множини X є її $\underline{R}$ -нижньою апроксимацією:

$$POS(X) = \underline{R}X. \quad (9)$$

Негативною областю X вважається така підмножина елементів U, які точно не належать до X:

$$NEG_R(X) = U - \overline{R}X. \quad (10)$$

Граничною областю X вважається така підмножина елементів U, які належать $\overline{R}$ -верхній апроксимації, та одночасно не належать до $\underline{R}$ -нижньої апроксимації:

$$BN_R(X) = \overline{R}X - \underline{R}X. \quad (11)$$

$$BN_R(X) = \{x \in U : 0 < \mu_X^R(x) < 1\}. \quad (12)$$

Цільова множина $X \subseteq U$ є R-точною (R-визначеною), якщо вона може бути виражена як об'єднання категорій виділених на U на основі заданого відношення еквівалентності R. В цьому випадку $\overline{R}X = \underline{R}X$, і як наслідок $BN_R(X) = 0$.

Цільова множина $X \subseteq U$ є R-неточною (R-грубою), якщо вона не може бути виражена як об'єднання виділених на U класів еквівалентності для будь-якого заданого $R \in IND(K)$. В цьому випадку $|\overline{R}X| > |\underline{R}X|$ та $BN_R(X) > 0$.

Розглянемо основні положення двоетапної процедури пошуку найбільш подібного до цільової ситуації прецеденту використовуючи комбінований підхід на основі методів ТГМ та *CBR*-підходу.

Припустимо, задана БПр $CL = \{Case_i \mid i = \overline{1,n}\}$, яка характеризує певну ПрО та прецедент, що характеризує поточну ситуацію $Case_{targ}$. Прецедент $Case_i \in CL$, $i = \overline{1,n}$ та цільовий прецедент $Case_{targ}$ відповідають моделі (1).

Задача полягає у звуженні вихідного набору прецедентів CL для подальшого пошуку такого $Case_j$, що в найбільшій мірі відповідає $Case_{targ}$.

На першому етапі відсікається частина прецедентів, що не відповідають визначеним умовам пошуку.

Якщо CL є індексованою БПр, тоді відповідно до заданої схеми індексації визначається така область $CL' \subseteq CL$, яка задовольняє параметрам поточної ситуації s.

Якщо CL є не індексованою БПр, тоді пропонується наступна схема грубої (попередньої) фільтрації прецедентів:

1) попередня ініціалізація: $CL' = \varnothing$;

2) для кожного параметру $p_l \in P$ цільової ситуації s, що описує прецедент $Case_{targ}$, задати межі інтервалу пошукового запиту $[a_l^s; b_l^s]$ такі, що $a_l^s \geq \min_l$,

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$b_l^s \le \max_l$, $a_l^s \le p_l(s) \le b_l^s$. Якщо межі інтервалу $[a_l^s; b_l^s]$ не задаються явним чином, тоді вони приймаються рівними мінімально можливому $\min_l$ та максимально можливому $\max_l$ значенню відповідного параметру p_l;

2) локалізації підпростору утвореного шляхом перетину площин, обмежених границями інтервалів $[a_l^s; b_l^s]$, для кожного $p_l \in P$ цільової ситуації s в m-мірному просторі;

3) визначення підмножини прецедентів $CL' \subseteq CL$, які за значеннями відповідних параметрів $p_l \in P$ прецеденту $Case_i \in CL$ потрапили до підпростору, обмеженого границями інтервалу $[a_l^s; b_l^s]$: якщо $\forall p_l \in P$ прецеденту $Case_i \in CL$ значення $p_l(Case_i) \in [a_l^s; b_l^s]$, то $CL' = CL' \cup Case_i$.

Розглянемо приклад пошуку прецедентів для випадку, коли для опису ситуації $Case_{targ}$ використовується два параметри p_1 та p_2 для яких було задано відповідні околиці в межах $[a_1^s; b_1^s]$ та $[a_2^s; b_2^s]$. Згідно до запропонованої процедури простір пошуку звужується до області утвореної перетином площин A та B, рис. 2. Подальший пошук здійснюється серед підмножини прецедентів {$Case_1$, $Case_7$}.

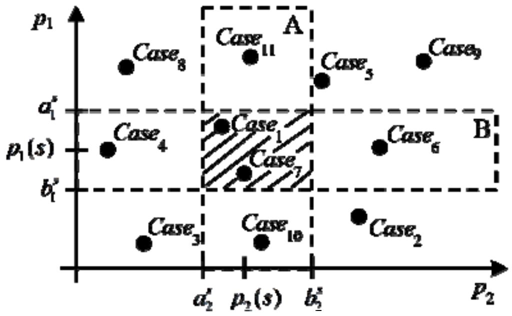

Рисунок 2 – Графічне подання процедури попередньої фільтрації прецедентів у двовимірному просторі

На другому етапі вирішується задача звуження доступної для аналізу множини $CL' \subseteq CL$, шляхом визначення апроксимацій заданої цільової множини прецедентів U_{targ}.

Виходячи із математичної нотації ТГМ, існуючу СЗн відносно значень параметрів ситуації s, яку описує прецедент $Case_i \in CL'$ можна подати у формі ІС виду $Sys = (U, P, V, f)$, де $U = CL'$; P – не порожня скінчена множина параметрів поточної ситуації s, відповідно до моделі (2); V – множина значень параметру $p_l \in P$, відповідно до моделі (2); $f \wedge U \times P \to V$ – інформаційна функція, така, що $\forall p_l \in P$, $Case \in U$, $f(Case, p_l) \in V_{p_l}$.

Якщо значення деякого параметру прецеденту є безперервною величиною, то для проведення подальшого аналізу воно має бути дискретизовано (виділені відповідні інтервали значень аналізованого параметру / атрибуту ІС). Дискретизація є обов’язковим етапом в процесі аналізу даних ІС, оскільки ТГМ не передбачає механізмів обробки числових атрибутів [27].

Процедура звуження множини $CL' \subseteq CL$ складається із реалізації наступних послідовних кроків:

1. Формування цільової множини прецедентів $U_{targ} \subset U$, $U_{targ} = \{Case_j \mid j = \overline{1,b}\}$, $b \ge |U|$, $U_{targ} \ne \varnothing$.

2. Виділення класів еквівалентності $\mathrm{E} = \{E_j \mid j = \overline{1,k}\}$ для заданої сукупності параметрів P.

3. Визначення $\overline{R}$-верхньої та $\underline{R}$-нижньої апроксимацій цільової множини U_{targ} відповідно до (4), (5), або (7), (8), якщо задана функція (6).

4. Визначення позитивної (POS_R), негативної (NEG_R) та граничної (BN_R) областей цільової множини U_{targ} відповідно до (9)–(12).

5. Звуження універсуму U за одним із наступних правил, $U' \subseteq U$:

$$U' = \begin{cases} U \setminus NEG_R(U_{targ}); \\ POS_R(U_{targ}); \\ POS_R(U_{targ}) \cup BN_R(U_{targ}). \end{cases} \tag{13}$$

У першому випадку виключаються із подальшого розгляду прецеденти, які із упевненістю не належать заданій цільовій множині U_{targ}. Це є відображенням песимістичного підходу до звуження вихідної множини прецедентів; у найгіршому випадку $NEG_R(U_{targ}) = \varnothing$.

У другому випадку розглядається оптимістичний підхід, який полягає у припущенні, що найбільш близький до аналізованої ситуації прецедент $Case_j$ належить області $POS_R(U_{targ})$. Але в цьому випадку відкидається з розгляду частка прецедентів $Case_j$, які потенційно (за певних умов) можуть належати заданій цільовій множині U_{targ}.

У третьому випадку пропонується таке правило звуження вихідної множини прецедентів, за яким $U' \subseteq U$ містить прецеденти, які належать або потенційно можуть належати цільовій множині U_{targ}.

6. Визначення найбільш близького прецеденту $Case_j \in U'$ до аналізованої ситуації $Case_{targ}$: $\min(d(Case_j, Case_{targ}))$, $\forall Case_j \in U'$, $1 \le j \le |U'|$, $d(Case_j, Case_{targ}) \in [0, 1]$.

Ступінь близькості між прецедентами $Case_j$ та $Case_{targ}$ визначається за заданою мірою відстані d, що є показником близькості між аналізованими об’єктами в деякому заданому метричному просторі.

На рис. 3 наведена узагальнена структурна схема процедури інтелектуальної підтримки процесів синтезу (пошуку, адаптації, прийняття) рішень на основі запропонованої модифікації CBR-підходу.

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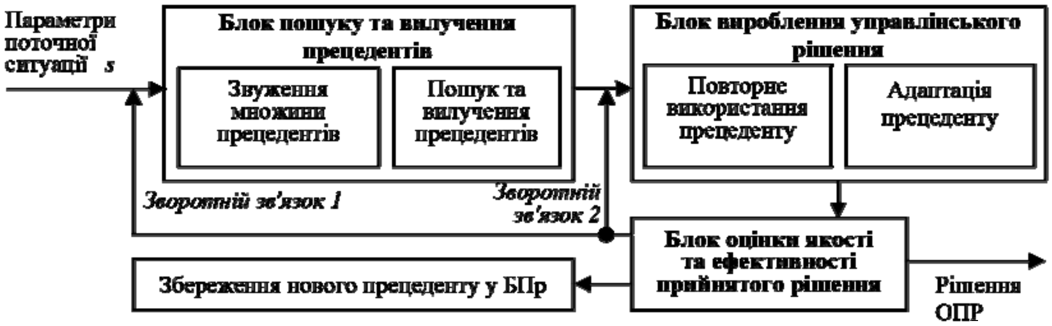

Рисунок 3 – Узагальнена структурна схема процесу пошуку прототипів рішень

В блоці *пошуку та вилучення прецедентів* на основі отриманого набору вхідних даних, що характеризує параметри поточної ситуації *s* виконується процедура попередньої фільтрації БПр та визначення підмножина прецедентів $CL' \subseteq CL$, що задовольняють попередньо визначеним параметрам пошуку за введеними обмеженнями за всіма (або з деякими) параметрами цільової ситуації. Наступним кроком є процедура звуження отриманої множини CL' відповідно до запропонованого в роботі підходу на основі методів ТГМ. Вихідна доступна для пошуку сукупність прецедентів $Case_i \in CL'$ відповідно до заданої цільової множини U_{targ} поділяється на підгрупи (сегменти), що відповідають позитивній (POS_R), негативній (NEG_R) та граничній (BN_R) областям заданої цільової множини U_{targ}. Такий поділ стає можливий за рахунок визначення верхньої та нижньої апроксимацій U_{targ}. Подальший пошук найбільш близького до заданої ситуації *s* прецеденту $Case_i$ може бути проведено в рамках наступних областей: POS_R, $CL \setminus NEG_R$ або ($POS_R \cup BN_R$), що в свою чергу дозволяє скоротити час пошуку близьких до поточної ситуації прецедентів. Далі відбувається процедура пошуку та вилучення прецеденту $Case_j$ в рамках визначеної підмножини прецедентів за обраним методом (на основі оцінювання міри подібності на множині параметрів, що використовуються для опису прецедентів і поточної ситуації; з урахування застосовності прецедентів; на основі знань експертів, та ін.).

В блоці *вироблення управлінського рішення* вирішується задача повторного використання вилученого прецеденту (за необхідністю адаптація прецеденту) для спроби вирішення поточної проблеми. За результатами вирішення однієї з цих двох задач відбувається інтерпретація отриманих результатів, виробляється управлінське рішення; оцінюється його якість та ефективність, здійснюється контроль та коригування. Оцінка якості (ефективності) рішення може проводитися на етапах його синтезу, прийняття або реалізації. Показниками якості прийнятого рішення можуть бути як кількісні, так і якісні індикатори, такі як своєчасність, економічна ефективність рішення, та ін. Якщо вироблене рішення не відповідає визначеним вимогам, то відбувається його коригування (зворотний зв'язок 2), або коригування цільової множини прецедентів (зворотний зв'язок 1). Новий прецедент, що описує сценарій вирішення поточної проблемної ситуації *s*, зберігається у БПр.

4 ЕКСПЕРИМЕНТИ

Розглянемо приклад діагностування ризику виникнення цукрового діабету на основі запропонованої в роботі модифікації *CBR*-підходу. Для опису *s* було виділено множину параметрів $P = \{p_l \mid l = \overline{1,15}\}$. Відповідно до шкали FINDRISC були виділені наступні параметри [28]:

p_1 – вікова група = {0 – менше 45 років; 2 – від 45 до 54 років; 3 – від 55 до 64 років; 4 – більше 65 років};

p_2 – індекс маси тіла = {0 – менше 25 кг/м^2; 1 – від 25 до 30 кг/м^2; 2 – більше 30 кг/м^2};

p_3 – окружність талії (чоловік / жінка)= {0 – менше 94/80 см; 3 – 94–102/80–88 см; 4 – більше 102/88 см};

p_4 – щонайменше 30 хв. щоденне фізичне навантаження = {0 – так; 2 – ні};

p_5 – вживання овочів у їжу = {0 – кожен день; 1 – не кожен день};

p_6 – вживання антигіпертензивних препаратів на регулярній основі = {0 – ні; 2 – так};

p_7 – підвищений рівень глюкози у крові = {0 – ні; 5 – так};

p_8 – сімейна історія діабету = {0 – відсутній у родичів; 3 – був у дідуся / бабусі, тітки, дядька, двоюрідного брата/сестри; 5 – був у мого батька, брата/сестри, власної дитини}.

Шкала FINDRISC використовується у людей віком від 25 років, та є ефективним інструментом оцінки ризику розвитку цукрового діабету 2 типу, включаючи безсимптомний перебіг цукрового діабету та порушення толерантності до глюкози.

Додатково було розглянуто перелік маркерів цукрового діабету відповідно до [29]:

p_9 – надмірний голод;
p_{10} – часте сечовипускання;
p_{11} – фруктовий запах дихання;
p_{12} – погане загоєння ран;
p_{13} – коливання ваги;
p_{14} – часті інфекції;
p_{15} – відчуття поколювання в стопах і пальцях.

Оцінювання параметрів $p_9 \div p_{15}$ здійснювалось на основі вербальної шкали з наступними градаціями: 0 – «Ні»; 1 – «Так».

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Таким чином, для опису БПр була використана параметрична модель виду:

$$Case_i = \{p_1, p_2, ..., p_{15}; d_i; r_i\}.$$

БПр містить 50 записів, які було сформовано на основі анонімного опитування респондентів ($x_1 \div x_{50}$).

Припустимо, поточна проблемна ситуація задана наступними значеннями:

$$S_{targ} = (p_1=2;\ p_2=1;\ p_3=3;\ p_4=2;\ p_5=0;\ p_6=2;\ p_7=5;\ p_8=0).$$

За результатами попередньої фільтрації БПр на основі введених обмежень (вікова група від 40 до 57 років; індекс маси тіла до 27 кг/м^2; окружність талії до 98/84 см) було виділено підмножину із 10 прецедентів, табл. 1.

Таблиця 1 – Вихідні дані, що характеризують параметри $p_1 \div p_{15}$ прецеденту $Case_i$

$Case_i$	Значення параметрів прецеденту														
	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}
$Case_1$	0	1	3	2	0	2	5	0	1	1	0	1	1	1	1
$Case_{12}$	2	1	3	2	1	0	3	0	1	0	0	1	1	1	1
$Case_{18}$	2	1	3	2	1	0	3	0	1	1	0	1	1	1	1
$Case_{24}$	0	0	0	0	1	0	0	3	0	1	0	0	1	1	0
$Case_{27}$	2	1	3	0	1	2	5	3	1	1	0	1	1	1	1
$Case_{31}$	3	0	0	2	1	0	0	0	1	0	0	0	0	1	0
$Case_{33}$	0	1	3	2	0	2	5	5	1	1	1	1	0	0	0
$Case_{38}$	3	1	3	2	1	0	0	5	1	1	0	1	1	1	1
$Case_{40}$	2	1	3	0	1	2	5	3	1	1	1	1	0	0	0
$Case_{49}$	0	1	3	2	0	2	5	5	1	1	0	1	1	1	1

Параметри прецеденту $Case_i$ формувались на основі оцінок респонденту x_i.

5 РЕЗУЛЬТАТИ

Відповідно до нотації ТГМ вихідні дані табл.1 можуть бути подані у формі ІС $Sys = (U, P, V, f)$, де $U = \{Case_i\}$ – не порожня скінчена множина елементів (універсум), $|U| = 10$; $P = \{p_l \mid l = \overline{1,15}\}$ – не порожня скінчена множина примітивних атрибутів (параметрів, що описують поточну ситуацію); $V_{p_l} \subseteq V$ – множина значень параметру p_l; f – інформаційна функція, така, що $\forall p_l \in P$, $Case \in U$, $f(Case, p_l) \in V_{p_l}$. На множині P виділено підмножини C і D такі, що $C, D \subset P$, де підмножина $C = \{p_i \mid i = \overline{1,8}\}$ являє собою множину параметрів, сформованих відповідно до шкали FINDRISC; підмножина $D = \{p_i \mid i = \overline{9,15}\}$ містить додаткові параметри (маркери цукрового діабету відповідно до [29]), що необхідні для формування цільової множини $U_{targ} \subseteq U$.

За даними табл.1 можна виділити наступні класи еквівалентності за значеннями параметрів $p_i \in C$:

$E_1=\{Case_1\}$; $E_2=\{Case_{12}, Case_{13}\}$;
$E_3=\{Case_{24}\}$; $E_4=\{Case_{31}\}$;
$E_5=\{Case_{27}, Case_{40}\}$; $E_6=\{Case_{33}, Case_{49}\}$;
$E_7=\{Case_{38}\}$.

Припустимо, що цільова множина U_{targ} містить такі x_i, для яких $\forall p_i \in D \setminus \{p_{11}\}: p_i = 1$; $p_{11} = 0$, що, відповідно до [29], відповідає ризику наявності цукрового діабету другого типу.

Таким чином, буде сформована наступна цільова множина:

$$U_{targ}=\{Case_1, Case_{18}, Case_{27}, Case_{38}, Case_{49}\},\ U_{targ} \subseteq U.$$

За даними табл.1 для $p_i \in C$ розрахуємо значення POS_R, NEG_R, BN_R, $\underline{R}U_{targ}$, $\overline{R}U_{targ}$ відповідно до сформованих класів еквівалентності $E_1 \div E_7$:

$POS_R(U_{targ}) = \underline{R}U_{targ} = \{Case_1, Case_{38}\}$;

$\overline{R}U_{targ} = \{Case_1, Case_{12}, Case_{18}, Case_{27}, Case_{33}, Case_{38}, Case_{40}, Case_{49}\}$;

$BN_R(U_{targ})=\{Case_1, Case_{12}, Case_{18}, Case_{27}, Case_{33}, Case_{38}, Case_{40}, Case_{49}\} - \{Case_1, Case_{38}\} = \{Case_{12}, Case_{18}, Case_{27}, Case_{33}, Case_{40}, Case_{49}\}$;

$NEG_R(U_{targ}) = \{Case_1, Case_{12}, Case_{18}, Case_{24}, Case_{27}, Case_{31}, Case_{33}, Case_{38}, Case_{40}, Case_{49}\} - \{Case_1, Case_{12}, Case_{18}, Case_{27}, Case_{33}, Case_{38}, Case_{40}, Case_{49}\} = \{Case_{24}, Case_{31}\}$.

Отже, із подальшого аналізу виключаємо підмножину $U' = \{Case_{24}, Case_{31}\}$, оскільки $NEG_R(U_{targ}) = \{Case_{24}, Case_{31}\}$.

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На основі метрики Евкліда, $\forall Case_i \in U \setminus U'$ обчислимо відстань $d(S_{targ}, Case_i)$ [30]:

$$d(S_{targ}, Case_i) = \sqrt{\sum_{j=1}^{15}\left(p_j^{S_{targ}} - p_j^{Case_i}\right)^2} . \qquad (14)$$

Ступінь подібності між поточною ситуацією (S_{targ}) та кожним $Case_i \in U \setminus U'$ визначається відповідно до виразу:

$$S_i = \left(1 - \frac{d(S_{targ}, Case_i)}{\sum\limits_{Case_i \in U \setminus U'} d(S_{targ}, Case_i)}\right) \cdot 100\% . \qquad (15)$$

За результатами проведених розрахунків, прецедент $Case_1$ (S_1 = 94 % подібності) є найбільш близьким до поточної проблемної ситуації S_{targ}. Необхідно відзначити, що прецедент $Case_1$ за оцінками параметрів $p_i \in C$ (табл. 1) було віднесено до позитивної області цільової множини ($Case_1 \in POS_R(U_{targ})$), що вказує на його однозначну приналежність до U_{targ}.

6 ОБГОВОРЕННЯ

Запропонована в роботі двоетапна процедура звуження вихідної множини прецедентів $Case_i \in CL$ передбачає попередню грубу фільтрацію прецедентів шляхом введення обмежень на значення параметрів прецедентів на першому етапі та додаткове звуження отриманої підмножини прецедентів методами ТГМ на другому етапі.

Запропонований алгоритм фільтрації прецедентів дозволяє відсікати частину БПр, яка не відповідає заданим граничним межам параметрів цільового прецеденту $Case_{targ}$, та не вимагає значних обчислювальних ресурсів. Проте необхідно зазначити, що запропонована процедура не враховує щільність розподілу прецедентів, таким чином може бути отримана порожня підмножина прецедентів $CL' \subseteq CL$, або навпаки, підмножина зі значною кількістю прецедентів, що в результаті позначиться на ефективності подальшого пошуку. Цей недолік може бути подолано шляхом пошуку оптимальних значень $[a_l^s; b_l^s]$, або застосування процедури індексації БПр з метою визначення підмножини $CL' \subseteq CL$. Іншим проблемним питанням є аналіз прецедентів, розміщених на межі, або у безпосередній близькості до межі підпростору, що містить множину прецедентів $CL' \subseteq CL$.

Запропонована в роботі процедура подальшого звуження, визначеної на попередньому кроці підмножини прецедентів CL', дозволяє розділити множину CL' на підгрупи, що відповідають позитивній (POS_R), негативній (NEG_R) та граничній (BN_R) областям заданої цільової множини U_{targ}. В основі запропонованого підходу лежить процедура формування цільової множини U_{targ} при побудові POS_R, NEG_R та BN_R областей. Цільова множина U_{targ} може бути сформована за визначеним переліком параметрів $p_l \in P$, або задана експертним шляхом.

В основу першого підходу може бути покладено вирішення задачі кластеризації атрибутів ІС *Sys* (які по суті є параметрами прецеденту $Case_i$). В цьому випадку репрезентативні атрибути (параметри $p_l \in P$), знайдені у кластерах, можуть бути використані для формування цільової множини U_{targ}.

Параметри $p_l \in P$, за якими було побудовано U_{targ} виключаються із розгляду при формуванні класів еквівалентності E_h та визначення областей POS_R, NEG_R, BN_R, $\underline{R}U_{targ}$, $\overline{R}U_{targ}$ цільової множини U_{targ}.

В якості іншого підходу до формування цільової множини U_{targ} може бути розглянута процедура вибору прецедентів за параметрами $p_l \in P$, що мають найбільше значення при аналізі поточної ситуації *s* (найбільше значення вагових коефіцієнтів $w_l \in W$, або значення $w_l \in W$ у заданому діапазоні).

Формування цільової множини U_{targ} на основі експертних переваг (на основі оцінок одного чи групи експертів) є більш суб'єктивним підходом і опирається на досвід і знання фахівця ПрО.

ВИСНОВКИ

У роботі розглянуті питання подання та виведення знань на основі прецедентного підходу та методів ТГМ; запропонована двоетапна процедура пошуку та вилучення прецедентів із БПр в основу якої покладено механізм попередньої фільтрації вихідної множини прецедентів за введеними обмеженнями на параметри цільової ситуації та додаткове звуження отриманої підмножини прецедентів на основі математичного апарату ТГМ.

В основі запропонованого підходу до звуження вихідної множини прецеденті, отриманої за результатами попередньої фільтрації БПр, лежить процедура її гнучкого сегментування за рахунок аналізу ступеню відповідності поточного прецеденту заданій цільовій множині прецедентів. До першого сегменту віднесено прецеденти, що в повній мірі відповідають заданій цільовій множині прецедентів; до другого сегменту віднесено такі прецеденти, які потенційно можуть належати визначеній цільовій множини; третій сегмент містить прецеденти, які із упевненістю не можуть належати заданій цільовій множині. Прецеденти, що належать до третього сегменту можуть бути із упевненістю виключені із подальшого розгляду та пошуку рішення.

Наукова новизна отриманих результатів полягає в тому, що дістав подальшого розвитку метод міркувань за прецедентами за рахунок комплексного застосування механізму фільтрації та методів ТГМ в процедурі пошуку прецедентів, що в найбільшій мірі відповідають параметрам цільової ситуації. Математичний апарат ТГМ дозволяє формувати додаткове розбиття БПр з метою вилучення із подальшого розгляду

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прецедентів, що не відповідають заданій цільовій множині.

Практична цінність полягає в тому, що запропонований підхід, дозволяє звузити вихідну множину прецедентів з метою скорочення часу пошуку прецедентів, які в найбільшому ступені відповідають параметрам поточної ситуації.

Перспективи подальших досліджень полягають у дослідженні підходів до формування цільової множини прецедентів.

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INTELLECTUAL SUPPORT OF THE PROCESSES OF SEARCHING AND EXTRACTION OF PRECEDENTS IN CASE-BASED REASONING APPROACH

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ABSTRACT

Context. The situational approach is based on the real-time decision-making methods for solving current problem situation. An effective tool for implementing the concept of a situational approach is an experience-based technique that widely known as case-based reasoning approach. Reasoning by precedents allows solving new (latest) problems using knowledge and accumulated experience of previously solved problems. Since cases (precedents) describing a scenario for solving a certain problem situation are stored in the case library, their search and retrieval directly determine the system response time. In these conditions, there is a need to find ways of solving an actual scientific and practical problem aimed at optimizing case searching and extracting processes. The object of the paper is the processes of searching and extracting of cases from the case library.

Objective. The purpose of the article is to improve the process of cases searching in CBR approach by narrowing down the set of cases permissible for solving the current target situation, and excluding from further analysis such cases that do not correspond to the given set of parameters of the target situation.

Method. The research methodology is based on the application of rough set theory methods to improve the decision-making procedure based on reasoning by precedents. The proposed two-stage procedure for narrowing the initial set of cases involves preliminary filtering of precedents whose parameter values belong to the given neighborhoods of the corresponding parameters of the target situation at the first stage, and additional narrowing of the obtained subset of cases by the methods of rough set theory at the second stage. The determination of the R-lower and R-upper approximations of a given target set of cases within the notation of rough set theory allows dividing (segmenting) the original set of cases available for solving the current problem stored in case library into three subgroups (segments). The search for prototype solutions can be performed among a selected subset of cases that can be accurately classified as belonging to a given target set; which with some degree of probability can be attributed to the given target set, or within the framework of the union of these two subsets. The third subset contains cases that definitely do not belong to the given target set and can be excluded from further consideration.

Results. The problem of presentation and derivation of knowledge based on precedents has been considered. The procedure for searching for precedents in case library has been improved in order to reduce the system response time required to find the solution closest to the current problem situation by narrowing the initial set of cases.

Conclusions. The case-based reasoning approach is received the further development by segmenting cases in terms of their belonging to a given target set of precedents uses methods of the rough set theory, then the search for cases is carried out within a given segment. The proposed approach, in contrast to the classic CBR framework, uses additional knowledge derived from obtained case segment; allows modeling the uncertainty regarding the belonging / non-belonging of a case to a given target set; removing from further consideration cases that do not correspond to a given target set.

KEYWORDS: situational management systems, rough set theory, case-based reasoning, case library, lower and upper approximation of the target set.

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ПРОГРЕСИВНІ ІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ

PROGRESSIVE INFORMATION TECHNOLOGIES

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CRITICAL CAUSAL EVENTS IN SYSTEMS BASED ON CQRS WITH EVENT SOURCING ARCHITECTURE

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ABSTRACT

Context. The article addresses the problem of causal events asynchrony which appears in the service-oriented information systems that does not guarantee that the events will be delivered in the order they were published. It may cause intermittent faults occurring at intervals, usually irregular, in a system that functions normally at other times.

Objective. The goal of the work is the comparison and assessment of several existing approaches and providing a new approach for solving the causal events synchronization issue in application to the systems developed using Command Query Responsibility Segregation (CQRS) with Event Sourcing (ES) architecture approach.

Methods. Firstly, the method of estimation of the likelihood of causal events occurring within the systems as the foundation for choosing the solution is suggested. Based on the results of the analysis of several projects based on CQRS with ES architecture it shows that the likelihood of critical causal events depends on the relationships among entities and the use-cases connected with the entities. Secondly, the Container of Events method, which represents a variation of event with full causality history, adapted to the needs of CQRS with ES architecture systems, was proposed in this work. The variants of its practical implementation have also been discussed. Also, the different solutions, such as Synchronous Event Queues and variation of Causal Barrier method were formalized and assessed. Thirdly, the methods described have been discussed and evaluated using performance and modification complexity criteria. To make the complexity-performance comparative assessment more descriptive the integrated assessment formula was also proposed.

Results. The evaluation results show that the most effective solution of the issue is to use the Container of Events method. To implement the solution, it is proposed to make the modifications of the Event Delivery Subsystem and event handling infrastructure.

Conclusions. The work is focused on the solution of the critical causal events issue for the systems based on CQRS with ES architecture. The method of estimation of the likelihood of critical causal events has been provided and different solutions of the problem have been formalized and evaluated. The most effective solution based on Container of Events method was suggested.

KEYWORDS: Service-Oriented Architecture, Event-Driven Architecture, Event Sourcing, Events synchronization, Domain Driven Design.

ABBREVIATIONS

CQRS is a Command Query Responsibility Segregation;
DDD is a Domain Driven Design;
DL is a Description logics;
EDS is an event-delivery subsystem;
ES is an Event Sourcing;
HSSM is a Halstead Software Science Metrics;
IoT is an Internet of Things;
SQL is a Structured Query Language.

NOMENCLATURE

α is a weight of integration complexity in comparison with maintenance complexity;
β is a weight of maintenance complexity in comparison with integration complexity;
Δ is a bounded lifetime of a broadcast message;
ε is a set of all events occurred in domain;
$\mathcal{N}$ is a set of all notifications – messages sent by all the publishers about the events;
ρ is a weight of performance in comparison with complexity;
τ_j is an interval of subscription;
a, b, c are events;
A is a certain type of events;
$\mathfrak{C}$ is a set of event types related to a subset of events;
C_i is a complexity of method's integration;
C_i is a clock function be Lamport;
C_m is a complexity of maintenance the system with integrated method;
$C(a)$ is a timestamp of the event a;
$C(A)$, $C(B)$, $C(H)$, $C(P)$, $C(S)$ are use cases connected with creation;
e^c_a, e^c_b are causal events connected with the creation of the instances;

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e_a^r, e_b^r are events connected with the removing of the instances;

e_a^m, e_b^m are events connected with the modification of the instances;

e_1, e_2, e_k are 1-st, 2-nd, k-th events;

E is a set of events of a distributed computation;

$E_{a+b+c}^{U_i}, E_{a+b}^{U_i}, E_{a+c}^{U_i}, E_a^{U_i}, E_b^{U_j}, E_c^{U_k}$ are event types for specific use case U_i

E_1, E_n are events of a distributed computation;

E_i is a subset of events of a certain type;

E_{int} is an integrated performance-complexity metric;

$h_{2+}, h_{2-}, h_{2.1}$ is a part of handler responsible for processing events $< e_1, e_2 >$ in Causal Barrier variant;

ex_2 is an exceptional situation when e_2 is lost or can be considered as lost after a defined period of time, i.e. bounded lifetime Δ has expired;

H_c is a set of command handlers;

H_e is a set of event handlers;

$H(b)$ is a causal history of the event b;

$H(Ej)$ is a set of handlers responsible for processing different combinations of events from the Ej group of events;

I_j is a subset of incoming events which j-th event handler r_j, is subscribed to;

k is a number of causal events within the Ej group;

l is an order of magnitude;

m is a modification function which denotes the applying transformations to the existing system;

$M(A)$, $M(B)$ are use cases connected with modification;

n is a number of connected events within the Ej group;

n_ℓ , n_u , m_ℓ , m_u are multiplicity coefficients;

n_k is a k-th notification;

n_1 is a represents the count of distinct operators;

n_2 is a represents the count of distinct operands;

N_1 is a total number of operators;

N_2 is a total number of operands;

$ntf()$ is a notify function;

O is a set of four basic interface operations;

P_{avg} is an average relative performance;

P_{hl} is an average high load performance;

P_{hpl} is an average high parallel load performance;

P_k is a relative performance of the k-th method;

P_i is a subset of the events published by w_i ;

P_{ll} is an average low load performance;

P_y is a set of all notifications published by the command handler;

$pub()$ is a publish function;

r is a remove predicate;

r_j is a j-th event handler;

$R(A)$, $R(B)$ are use cases connected with removing;

$s, t, u, v, u', v', u'', v''$ are time markers;

s_A is a subscription to A-type events;

S_x is a set of active subscriptions for event handler;

$sub()$ is a subscribe function;

T_k is a represents the time metric;

$T_{\min}$ is a represents the lowest time metric across all compared metrics;

$U_i(A)$, $U_i(B)$ are use case;

$usub()$ is a unsubscribe function;

w_i is a i-th command handler;

w, w_1, w_2 are worlds, using Kripke semantics;

W is a set of worlds, using Kripke semantics;

$\Box$ is a necessary truth;

$\Diamond$ is a possibility;

$\neg\Diamond$ is a impossibility.

INTRODUCTION

Development of the Modern software is an essential part of any business which helps to increase productivity, reduce costs, and improve customer services. But the modern business is always under the influence of changing business rules, adding new activities, modifications of procedures and processes. Thus, the systems developed as a business infrastructure should be flexible enough to be adapted to business and system requirements changes as quickly as possible. To handle this challenge different approaches [1], principles [2] and architectures [3–6] are provided.

One of the effective solutions is to build the system using event-driven architecture [4] which is based on Publisher-Subscriber pattern [7] of communication. It allows to enable indirect communication between modules (usually cloud services [5, 6]) using an intermediate infrastructure called Event Publisher which is responsible for delivering the messages published by the publishers to the subscribers. And thus, it allows to increase the level of flexibility [8] and scalability of the system.

Whilst event-driven and service-oriented architectures offer advantages at the system level, the combination of the Command Query Responsibility Segregation (CQRS) with Event Sourcing (ES) architectural design patterns is frequently employed in such systems to enhance application-level performance [9–11].

CQRS [12] is a design pattern that separates the command (write) side of an application from the query (read) side. CQRS is used in conjunction with ES [13] to provide a clear separation between the handling of commands that change the application state and the retrieval of data for querying. During a write operation, events are recorded in the event store, and the client is informed that the source of truth of the system has been updated, and eventually [14], the other parts of the system (e.g. projections [15], services) will be updated. The projections, which are denormalized data representations stored in the format requested by the client, are eventually updated by the event handlers subscribed to certain events. Projections may be based on SQL or NoSQL databases, or even pre-rendered web pages.

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The main advantages of CQRS with ES architecture are as follows. Write operations are performed quickly in comparison to the non-CQRS systems, because the execution of the commands does not depend on database manipulation, and data manipulation is restricted only to saving events, which appear in the result of the command execution, to the Event Store. Read operations are reduced to selecting pre-prepared data causing significant speed-up of user query processing. Clear separation of concerns between commands and queries, facilitating a more modular and maintainable codebase.

The CQRS with ES architecture is the most applicable for systems that are based on events on a business level, e.g. trip systems, financial systems [16]. But this architecture is not applicable to systems that require a strong degree of temporal consistency [17].

The systems based on CQRS with ES architecture can also use the Publisher-Subscriber pattern to realize flexible, indirect communication between command handlers, which are the producers and publishers of the events, to the event handlers, which are the subscribers of the events.

The object of the study is a causal events phenomenon which appears in information systems.

One of the important problems which appears in the systems based on CQRS with ES architecture which uses Publisher-Subscriber pattern for enabling indirect communication between command handlers and events handlers is the problem of synchronization of causal events. Causal events are causally related events the order of which should be preserved, i.e. the events connected by happened-before relationship [18, 19]. The source of the problem is the fact that the event delivery subsystem does not guarantee that published events will be delivered in the order they were published. It may cause intermittent, hardly detected faults occurring at intervals, usually irregular, in a system that functions normally at other times. The existing solutions of this problem are not formalized and evaluated, the likelihood of appearance of the issue is not well understood. Therefore, to provide an effective solution to this problem, preserving the maintainability level of the system, it is necessary to study and evaluate the existing methods of the solution.

The subject of the study is the issue of synchronization of causal events in systems based on CQRS with ES architecture.

The purpose of the work is evaluating the likelihood of the appearance of causal events in systems based on CQRS with ES architecture and provide the most effective method of the solution to the problem based on the results of the evaluation of different existing and novel solutions using complexity and performance criteria.

1 PROBLEM STATEMENT

Among several well-known problems connected to CQRS with ES architecture [20, 21] the problem of critical causal events synchronization has not been fully studied. Perhaps, the reason is that using Publisher-Subscriber pattern is not only one way to realize the communication between Write and Read subsystems. The source of the problem is connected to Publisher-Subscriber pattern and inability of the event delivery subsystem to guarantee the preservation of the order of published events, i.e. that published events will be delivered in the order they were published. It may cause intermittent synchronization faults which are considered as one of the most difficult problems in distributed programming [22].

The main phases of the typical workflow of the command processing by the system built using CQRS with ES architecture and Publisher-Subscriber pattern-based communication subsystem considered in this paper are as follows (See Fig. 1).

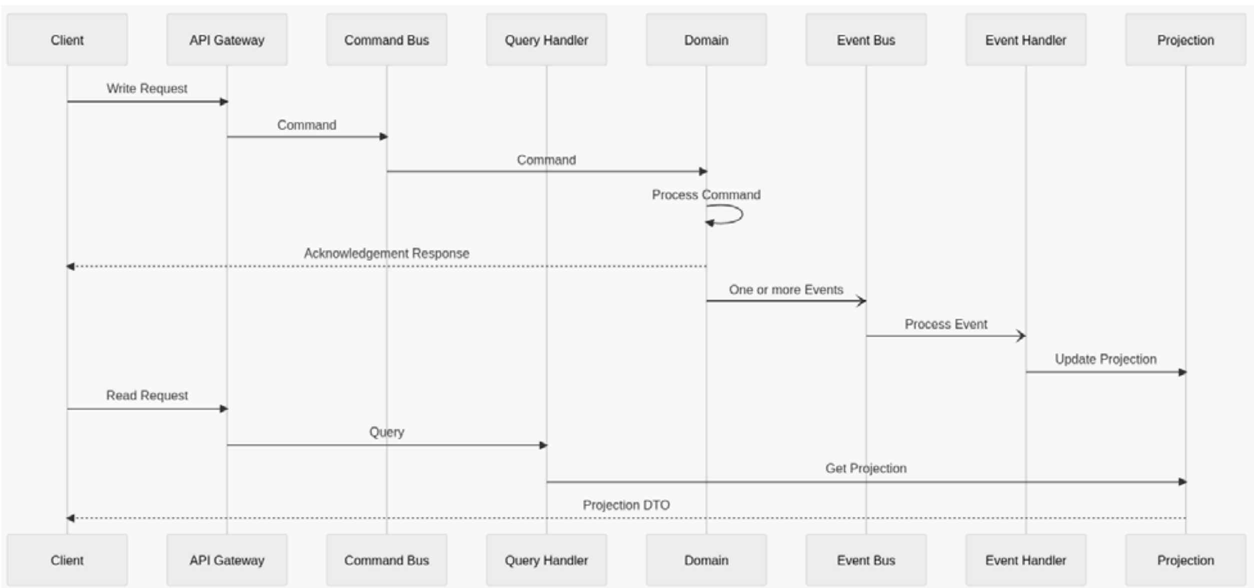

Figure 1 – The typical workflow of the command processing by the CQRS with ES system

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After the request validation, the command enters a command handler, a certain component of the application business logic layer responsible for processing the request. The command handler uses repositories to retrieve an aggregate or some aggregates (domain layer entities) needed to perform the task. Then it calls a method or some methods of the aggregate [23]. In response, aggregate generates domain events which reflect the changes of the state of the aggregate.

Domain events are accepted and then put by the command handler to the Event Store unit responsible for saving and, publishing those events to Event Bus (the module responsible for delivery of the messages to subscribers, i.e. event handlers).

Event handlers subscribed to the different types of events receive and process published events. Some of the event handlers could be responsible for notification delivery, others for dynamic reports preparation (projections), etc.

Following [24] formally the system can be described as a tuple.

$$\left\langle H_c, H_e, \bigcup_{x \in H_e} S_x, P_y, \mathcal{N}, \mathcal{E}, E, T, \mathfrak{C}, O \right\rangle.$$

H_c is a set of command handlers responsible for processing incoming commands and publishing the notifications to event-delivery subsystem (EDS); H_e – a set of event handlers subscribed to notifications sent by the EDS; $\mathcal{E}$ – the set of all events occurred in domain; $\mathcal{N}$ – the set of all notifications – messages sent by all the publishers about the events; $E: \rightarrow \mathcal{E}$ – a unary function that maps a notification to the event the notification represents; $\mathfrak{C}$ – the set of event types related to a subset of events, and used to restrict the scope of variables, control the formation of expressions, and classify expressions by value [25]; $T: \mathcal{E} \rightarrow \mathfrak{C}$ – a function that maps an event to the event type, consiquently the notifications could also be mapped to event types using the composition of functions E and T, so we can say that $\mathfrak{C}$ represents the set of notification types as well; S_x – is a set of active subscriptions for event handler $x \in V$, where one subscription relates to a specific type of events; P_y – is a set of all notifications published by the command handler $y \in H_c$; O – a set of four basic interface operations [26] which can be defined as follows.

$pub_i^u(n_k)$ – notification $n_k \in \mathcal{N}$ related to event $e_k \in \mathcal{E}$ (which happened in domain) is published by the i-th command handler $w_i \in H_c$ to EDS at time u, that means that not all domain events obtained in result of command execution may be transformed to notifications and published by the command handler to EDS, but all the notifications are mapped to the events, $sub_j^t(A) \Leftrightarrow s_A \in S_{r_j}$ – event handler $r_j \in H_e$ can be subscribed to notifications about the events of a certain type $A \in \mathfrak{C}$ at time t. The result of the operation is the subscription added to a set of active subscriptions of the r_j , i.e. $s_A \in S_{r_j}$ Following [27] we can define the subscription $s_A \in S_{r_j}$ as a predicate: if the notification n_k matches the topic (or channel) of subscription (in our case the channel is related to notification type A), i.e. if $n_k : A$, then $s_A(n_k) \equiv \top$, and then the notification will be delivered to the event handler r_j at time $v > t$, denoted by $nfy_j^v(n_k)$, otherwise $s(n_k) \equiv \bot$, and the event will not be delivered to r_j .

$nfy_j^v(n_k)$ – is the operation of delivery of the notification. Thus, if j-th event handler is subscribed to notifications of A type, and the notification of that type is published by a publisher (we use '_' index to show the independency of command handler).

$$n_k : A \wedge pub_{\_}^u(n_k) \wedge s_A S_{r_j} \Leftrightarrow nfy_j^v(n_k), v > u. \quad (1)$$

$usub_j^t(A) \Rightarrow s_A \notin S_{r_j}$ – event handler $r_j \in H_e$ can be unsubscribed from notifications about the events of a certain type A at time t, the result of the operation is the subscription excluded from the set of active subscriptions of the r_j .

This model does not reflect all the specific features of the system (e.g. events storing, replay mechanisms etc.) and is focused on the components connected with critical causal events issue.

It should be noted that inspire the difference of the meaning of the event and the notification terms we are intended to use only event term denoting the events passed by the command handler to EDS and then delivered to subscribers. Formally the problem can be described by the time diagram shown in Fig. 2.

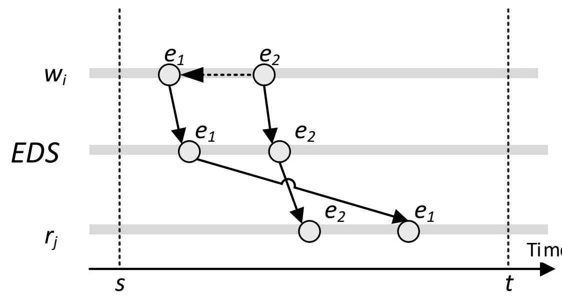

Figure 2 – A time diagram of a distributed computation

In the diagram command handler $w_i \in H_c$ in result of a command processing passes two events e_1, e_2 to the EDS, the dotted line shows that e_2 is an effect of e_1 , i.e. e_1 is the cause of e_2 . The projection of position of the events on the Time-axis shows their temporal relation as follows: $pub_i(e_1) \prec pub_i(e_2)$, i.e. publishing of e_1 by

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w_i precedes publishing of e_2 by the same w_i command handler, "$\prec$" denotes strict partial order relation. Another way to denote the relation is $pub_i^u(e_1) \wedge pub_i^v(e_2)$, where $e_1, e_2 \in \varepsilon$, $s \le u \le v \le t$ and $s,u,v,t \in \mathcal{T}$, $\mathcal{T}$ is the set of the clock's ticks.

$e_1, e_2 \in P_i \cap I_j$, where P_i – a subset of the events published by w_i, I_j – a subset of incoming events which j-th event handler $r_j \in R$, is subscribed to, i.e. $P_i, I_j \subseteq \mathcal{N}$.

The interval of subscription $\tau_j(s_A, s, t) \in S_{r_j}$ of j-th event handler r_j to events of type A is an interval between subscription occurred at time s that can be denoted as $sub_j^s(A)$ and unsubscription occurred at time t denoted by $usub_j^t(A)$, s and t are timestamps, i.e. $s,t \in \mathcal{T}$ and $s < t$.

It means that if $e_k : A$ matches the subscription s_A in the defined interval τ_j, and the e_k is published by a command handler at time $s < u < t$, then the event will be necessarily delivered to the event handler r_j by the EDS and reversely, if the event is delivered then it was published by a command handler and matches the subscription in the defined interval. Formally this assertion can be described by the following formula.

$$e_k : A \wedge \tau_i \in S_{r_j} \wedge pub_{-}^{u}(e_k) \Leftrightarrow \Box\, nfy_j^{u'}(e_k), \qquad (2)$$

where $s \le u < u' \le t$ and $s,u,u',t \in \mathcal{T}$. We use the necessitation operator $\Box$ from modal logic in this formula to underline the restrictions of the model applied to the systems under consideration, because in different real systems the inviolability of the rule seems doubtful.

The formal description of the problem using modal logic [29] can be represented by following formula:

$$\tau_j^A, \tau_j^B \in S_{r_j} \wedge pub_i^u(e_1) \wedge pub_i^v(e_2) \Rightarrow \Box\left[\left(nfy_j^{u'}(e_1) \wedge nfy_j^{v'}(e_2)\right) \vee \left(nfy_j^{u''}(e_1) \wedge nfy_j^{v''}(e_2)\right)\right] \qquad (3)$$

where

$$\tau_j^A \equiv \tau_j(s_A, s, t), \tau_j^B \equiv \tau_j(s_B, s, t), e_1 : A, e_2 : B, \qquad (4)$$

$$s \le u < v < v' < u' \le t \text{ and } s \le u < v < u'' < v'' \le t$$
$$s,u,v,u',v',u'',v'',t \in \mathcal{T}.$$

This formula can be interpreted using Kripke semantics [30] as follows. For a model with worlds (states) w_1, w_2 accessible from actual world w, it is true that:

$$w_1 \models \tau_j^A, \tau_j^B \in S_{r_j} \wedge pub_i^u(e_1) \wedge pub_i^v(e_2) \Rightarrow \Box\left[nfy_j^{u'}(e_1) \wedge nfy_j^{v'}(e_2)\right] \qquad (5)$$

$$w_2 \models \tau_j^A, \tau_j^B \in S_{r_j} \wedge pub_i^u(e_1) \wedge pub_i^v(e_2) \Rightarrow \Box\left[nfy_j^{u''}(e_1) \wedge nfy_j^{v''}(e_2)\right] \qquad (6)$$

Which implies

$$w \models \tau_j^A, \tau_j^B \in S_{r_j} \wedge \left(pub_i^u(e_1) \wedge pub_i^v(e_2)\right) \Rightarrow \Box\left[\left(nfy_j^{u'}(e_1) \wedge nfy_j^{v'}(e_2)\right) \vee \left(nfy_j^{u''}(e_1) \wedge nfy_j^{v''}(e_2)\right)\right] \qquad (7)$$

$w, w_1, w_2 \in W$.

It means that for the system in w there could necessarily be one of the situations, i.e. accessible worlds w_1 and w_2, in which the events are delivered in the order they have been published (w_1 case) and – the reverse situation (w_2 case).

The consequence of this is:

$$w \models \tau_j^A, \tau_j^B \in S_{r_j} \wedge \left(pub_i^u(e_1) \wedge pub_i^v(e_2)\right) \Rightarrow \Diamond \left(nfy_j^{u'}(e_1) \wedge nfy_j^{v'}(e_2)\right) \qquad (8)$$

which means that the systems under consideration allow the situation when the causal events are not delivered in the order they have been published. Here the existential modality operator $\Diamond$ denotes the possibility of the situation.

It is worth to note that for some event handlers the order of handling causal events is not critical, and the interpretation of the identified problem mostly depends on the system configuration.

Let us see two examples of the projects where this issue is acutely expressed.

The first example is the clinic information system. The clinic specializes in surgery operations, including emergent surgery, but also provides consulting services. Each Hospitalization instance should refer to an instance of the Patient class, but in some cases (for example, emergent) the Hospitalization can be created as a result of the ResisterPatientWithHospitalization command execution. The appropriate command handler triggers the creation of the Patient aggregate and calling its AddHospitalization method. In result, command handler reads PatientCreated and HospitalizationCreated domain events from the Patient aggregate and passes them to EDS in <PatientCreated, HospitalizationCreated> order.

The application that uses the API reacts to the HospitalizationCreated event by checking the existence of the Patient instance and if it does not exist in a cache, it causes the error. But in the case of an EDS that does not guarantee the order, the events that were published in order <PatientCreated, HospitalizationCreated> can be delivered in order <HospitalizationCreated, PatientCreated> causing the error.

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Another example is a financial system, where the broker is the owner of the group of users. Each broker must be connected with the group, but the group can be temporarily without an owner (this exceptional case can happen when the broker leaves the system for some reason). As a rule, the creation of the group is part of the broker creation process, but it could be the situation when the broker is assigned to the existing group which was owned by another broker. Thus, when a user adds the broker, the system can generate at least two variants of event sequences: <GroupCreated, BrokerCreated>, <BrokerCreated>. And, as in the previous example, it could cause an error in case of reverse order of delivered events.

Thus, this paper is devoted to resolving of these types of issues.

The solution of the problem of critical causal events synchronization depends on the solution of three main tasks which are as follows:

1) Providing a method of assessment of the likelihood of the issue which can be used to estimate the risks of critical causal events issue and to choose a proper strategy to address the issues discovered.

2) Providing a complex of methods and strategies to solve the issues considering the experience for handling the related problems in distributed information systems.

3) Providing a method of evaluation of effectiveness of the methods using the complexity and performance metrics.

2 REVIEW OF THE LITERATURE

The problem of synchronization of causal events was first addressed by L. Lamport [18]. In his paper he discussed the partial ordering defined by the "happened before" relation which is accepted by the researcher's community as the definition of "causality". In accordance with Lamport

Definition 1:

The "happened before" relation, in literature after Lamport denoted by →, is the smallest transitive relation that satisfies the following properties for any two events:

1) If a and b are events in the same process p_i, and a comes before b, then $a \rightarrow b$.

2) If a is the sending of a message (send event) by one process p_i and b is the receipt of the same message (receive event) by another process p_j, then $a \rightarrow b$.

3) If $a \rightarrow c \rightarrow \dots \rightarrow b$ then $a \rightarrow b$.

Happened before is strict partial order relation ($\prec$) which is irreflexive, asymmetric and transitive [22]. Thus, $a \rightarrow b \Leftrightarrow a \prec b$.

Firstly, it is worth to note that Lamport wrote that this relation could be interpreted as that it is possible for event a to causally affect event b. Thus, the relation shows only causality potential, not true causality.

Secondly, the second property of the relation is very important for understanding the methods suggested to resolve problems of causality in distributed computing. According to [22] a send event reflects the fact that a message was sent; a receive event denotes the receipt of a message together with the local state change according to the contents of that message. A send event and a receive event are said to correspond if the same message that was sent in the send event is received in the receive event. It is also assumed that a send event and its corresponding receive event occur in different processes.

The presented semantics of event and a message term is slightly different from the semantics used in event-driven architecture, Publisher-Subscriber pattern [28], software systems, where the event is a signal emitted by a component upon reaching a given state, which carries an information about the fact of state changed and can be broadcasted to the processes subscribed to such type of events. The message contains a request or command, and it is point-to-point interaction oriented.

Lamport gave a distributed algorithm for extending it to a consistent total ordering of all the events which is based on logical clocks. Each process has its own clock function C_i that assigns a number (timestamp) $C_i(a_k)$ to event a_k in that process and $a \prec b \Rightarrow C(a) < C(b)$. Lamport's algorithm has well-known restriction $C(a) < C(b) \nRightarrow a \prec b$ to overcome which several approaches (e.g. vector clocks) were suggested [31, 32]. These methods relate to different restrictions and limitations. For example, in [22] assumed that each process is strictly sequential, and the events of the process are totally ordered by the sequence of their occurrence. According to [33] a set of vector timestamps, one per event, cannot fully characterize a distributed computation in the systems that allow message "overtaking". According to [34] these methods can only be used when the number of processes is known by every process, so each process can be assigned an integer number as an identifier.

Considering that causality is "cause-effect" connection of phenomenon through which one event (cause) under certain conditions gives rise to another event (effect) [22] and the true causality of events can only be denoted explicitly [35, 36].

There are two basic classes of methods connected with explicit definition of the events causality.

The first class of methods is based on using the causal history of events, which can be defined as follows [22]:

Definition 2:

Let $E = E_1 \cup ... \cup E_n$ denote the set of events of a distributed computation and let $a, b \in E$, $a \neq b$ denote events occurring in the course of that computation.

The causal history of b, denoted $H(b)$, is defined as $H(b) = \{a \mid a \in E, (a \xrightarrow{c} b)\} \cup \{e\}$. Where $\xrightarrow{c}$ denotes true causality relation. The projection of $H(b)$ on E_i, denoted $H(b)[i]$, is defined by $H(b)[i] = H(b) \cap E_i$.

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It is worth to note that according to [22] E_i denotes the subset of events occurring at process p_i, while in the context of this work, E_i denotes a subset of events of a certain type, a subset defined by the characteristic predicate P_i, i.e. $E_i = \{a \mid P_i(a), a \in E\}$.

Definition 3:

Causality and causal history are related as follows:

$$1)\ a \xrightarrow{c} b \ \ iff \ \ a \in H(b). \tag{9}$$

$$2)\ a \parallel b \ \ iff \ \ a \notin H(b) \wedge b \notin H(a). \tag{10}$$

That means that causality relation is defined by the causality history.

The history of events can be represented differently depending on the specific of problems to be solved. For example, to solve the problem of causality tracking for distributed key-value stores in [36] proposed to describe the history by dotted version vectors etc. But the main idea is to attach causal history to the messages (in our case events) passing through the nodes-processes.

The simple way is to attach full causal history to each event, as it is proposed in [37]. Thus, the receiving process knows the order of events and waits for the completion of the causal event before reacting to the consequential one. The disadvantage of the method is the increasing of size of the additional information attached to the event. To reduce the size of payload a set of methods based on causal barrier has been proposed. These methods propose carrying information about the immediate predecessors of the event. This minimal information constitutes the so-called causal barrier of a message [34]. In [38][34] discussed a special type of causal broadcast, called Δ-causal broadcast, that can be used when the broadcast messages have a bounded lifetime Δ.

The second class of methods is based on an information protocol which allows to handle the causality of events specifying the information dependencies between the messages-communications that processes (agents [35]) may send. An agent may send a message-communication only if the state of the agent, which is based on the communication history, and the message-communication together satisfy the relevant information dependencies.

This approach is represented in works of Munindar P. Singh [35], who proposed a declarative, multi-agent approach based on true causality called information protocols. According to his works, the business process consists of a sequence of protocols, and each protocol reference must have at least one key parameter in common with the protocol in which its declaration occurs.

Another variant is to use communication protocols for point-to-point or multicast communications which enforce only a causal delivery order [39] that means that the delivery of messages has to be delayed according to causality constraints.

Among different types of distributed systems, the systems built using Publisher-Subscriber (Pub/Sub) pattern are the closest to the systems considered in this paper. Publishers and subscribers are interconnected by means of the so-called Notification Service, which plays a mediating role by storing the incoming subscriptions and routing incoming notifications towards the right destinations. For scalability reasons the notification service can be implemented in a distributed manner [40]. In [41] presented the basic operations classification, conditions and a Fault Model connected to Publisher-Subscriber systems which considers the problem of ordering.

In order to implement the causal order of published messages, in [28] apply causal barriers, but in comparison with the classical it does not enforce the causal order based on the identifiers of the nodes (per node vector) but by using direct message dependencies, which renders the algorithm more suitable for dealing with node dynamics. Thus, each *causal barrier[t]* keeps information on all messages that are predecessors of the next message that will be published by node *i* for topic *t*; the causal barrier consists thus of a set of message identifiers of format $\langle s, c\rangle$ (source and sequence counter).

In conclusion it should be highlighted that there are no well-known works connected with resolving the problem of critical causal events in the systems based on CQRS with ES architecture using Pub/Sub pattern to interact with the event handlers. The existing, described solutions depends on the specific of the problems they have been developed for, which makes it difficult to apply them directly to the problem under consideration.

The solution described in [35] has many similarities with the Saga pattern [42], suggested to address distributed transaction tasks and widely employed in information systems, for cases when modifying one aggregate leads to creating a command for modifying another aggregate. However, the considered issue arises when synchronizing causal events generated by changes to a single aggregate. While this approach could be applied in this situation, it would lead to suboptimal commands structure and performance degradation.

The solution provided in [37] is adapted to distributed virtual environment and cannot be directly applied to the systems under consideration. Additionally, it's not well understood how the authors resolve the problem with transitive events (i.e. $a \to c \to b$), and the case $a \to b \wedge a \to c \Rightarrow b \parallel b$ and $a \to c$ when the events *b* and *c* can be processed concurrently after the event *a* has been processed. Also, there is no information on how process sends the message to the process which is interested in only one event from the causal events package.

3 MATERIALS AND METHODS

The assessment of the likelihood of the causal events could help us not only to evaluate the risks connected to the issue, but also affects the choice of a method to manage the risks and to resolve the problem.

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Based on research across several projects based on CQRS with ES architecture and Publisher-Subscriber pattern-based communication subsystem, conducted at DBB-Software company [43], where causal events issue was most acutely felt, the following dependencies has been identified.

It was noticed that the likelihood of the issue is contingent upon the interdependence of associated entities within the aggregate (Fig. 3) and the relation of the use cases connected with the entities. We preferably focused our attention on the aggregation relationships between the entities of 1–0..* and 1–1..* multiplicity as the most common sources of the causal events issue in the examined projects. It worth recalling that multiplicity in UML describes how many instances of one class can be connected to an instance of another class through a given association.

Let us consider the following example. In a clinical information system, a patient record can include information on several hospitalizations (at least one) and all the hospitalizations must be connected to a certain patient. In other words, the instance of patient aggregate must be associated with at least one instance of the hospitalization (association of 1–1..* multiplicity).

Thus, in result of CreatePatient command execution we may say that the patient creation event (PatientCreated) causes the hospitalization creation domain event (HospitaliztionCreated). On the other hand, a patient may not require surgery (i.e. the multiplicity of the "hospitalization-surgery" association is 1–0..*). In this case, the attached hospitalization information may not contain any information about surgery planning, etc. Thus, the likelihood of causal events in this case is rather lower than in the variant of 1–1..* association, but is not impossible.

To formalize the association, we use DLR description logic [44] which is the most suitable formalization mechanism (e.g. in comparison to [45]) for representing domain entities by means of concepts and relations. Description logics (DL) are regarded as late descendants of Minski's frames [29] with an explicit model-theoretic semantics. There are a number of automated reasoning systems, that have been successfully applied to various application domains.

According to [44] an aggregation *A*, saying that instances of the class *C*1 have components that are instances of the class *C*2, is formalized in DLR by means of a binary relation *A* together with the following assertion (Fig. 4):

$$A \sqsubseteq (1{:}C1) \sqcap (2{:}C2). \quad (11)$$

Figure 3 – The typical example of relations between entities causing causal event issue

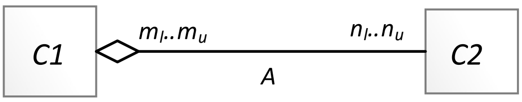

Figure 4 – Aggregation in UML [44]

The following convention is used: the first argument of the relation is the containing class (*C*1). The first component of the association is *C*1, the second is *C*2.

The multiplicity of an aggregation is expressed in DLR as follows.

$$C1 \sqsubseteq (\geq n_l[1]A) \sqcap (\leq n_u[1]A), \quad (12)$$

$$C2 \sqsubseteq (\geq m_l[2]A) \sqcap (\leq m_u[2]A). \quad (13)$$

If $n_\ell = 0$, i.e., the association is optional, the first conjunct could be omitted, and if $n_u = *$ (infinity) the second one is omitted.

Thus, using the example shown in Fig. 3. we can define following formulas.

$$Patient \sqsubseteq (\geq 1\ [1]hasHospitalization), \quad (14)$$

$$Hospitalization \sqsubseteq (=1\ [2]hasHospitalization). \quad (15)$$

where $=1\ [2]hasHospitalization$ is simplified variant of $\geq 1\ [2]hasHospitalization \sqcap \leq 1\ [2]hasHospitalization$

$$Hospitalization \sqsubseteq ([1]hasSurgery), \quad (16)$$

$$Surgery \sqsubseteq (=1[2]hasSurgery). \quad (17)$$

Before we start examining the use cases connected with the entities, we should formulate the restrictions and the specific of using terms and concepts.

Rigorously use case can be represented as a function which maps the request (in our case the request relates to command) into response and changes of the state of the system. Firstly, the function may map the request to different responses depending on the request content and the state of the system. Secondly, the function can be composed of other functions, considering different alternatives, i.e. $\lambda x.g(f(x)) : A \rightarrow C$ where $f : A \rightarrow B$ and $g : B \rightarrow C$. In accordance with Type theory [46] these functions can be described by the dependent functions (general productions) type denoted by $\Pi x{:}\ A.B(x)$, which means that if *A* is a type, we may have the family of types $B(x)$ where $x{:}\ A$.

Understanding the above specific, considering the works devoted to use cases formalization [47, 48], but guided by the purposes of the work trying to avoid unnecessary complexities connected to formulas representation, we should declare the following restrictions. Firstly, in this paper we are focusing only on the use cases related to the entities thus connected to three main operations (create, modify, remove). Secondly, we restrict the further using of the use case term to only the basic scenario omitting the exceptions, regarding only

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conditional success-oriented alternatives (e.g. alternatives which may trigger the use case extension connected with the other entity).

Three basic use cases connected with the create operation for the entities shown in Fig. 3 are as follows: CreatePatient, CreateHospitalization, CreateSurgery (in real system the names of use cases can be different, considering the requirements dictated by the ubiquitous language used to design the software).

Table 1 – Relations between use cases

Relation	Meaning
$C(P)\xrightarrow{inc}C(H)$	*C*(*P*) always invokes *C*(*H*)
$C(S)\xrightarrow{ext}C(H)$	*C*(*H*) invokes C(*S*) only when a condition is met, not always
$C(P)\xrightarrow{pre}C(H)$	*C*(*H*) cannot be invoked if *C*(*P*) was not invoked before
$C(H)\xrightarrow{pre}C(S)$	*C*(*S*) cannot be invoked if *C*(*H*) was not invoked before

Let us denote CreatePatient use case as *C*(*P*) (i.e. a successful path of the create patient scenario) CreateHospitalization as *C*(*H*), CreateSurgery as *C*(*S*).

The possible relations [49] between the use cases in accordance with the described model (Fig. 3) are presented in Table 1. To simplify the representation the relations are denoted as follows: the relation "*C*(*A*) includes *C*(*B*)" as $C(A)\xrightarrow{inc}C(B)$, the relation "*C*(*B*) extends *C*(*A*)" as $C(B)\xrightarrow{ext}C(A)$ the relation "*C*(*A*) precedes *C*(*B*)" as $C(A)\xrightarrow{pre}C(B)$. It is worth to note that in according with terminology [50] in the relations "*C*(*P*) includes/precedes *C*(*H*)" – *C*(*P*) called the base use case, while in the relation "*C*(*H*) extends *C*(*H*)" – the base use case is *C*(*H*).

Let us denote hasHospitalization relation with the multiplicity in direction from *Patient* to *Hospitalization* as <*P, H*>+ (here "+" denotes 1..*) and the same association in opposite direction as <*H, P*>, analogically hasSurgery relation as <*H, S*>*, where "*" denotes 0..* multiplicity.

Let us denote PatientCreated event as e_p^c, HospitalizationCreated as e_h^c and SurgeryCreated as e_s^c. The relation $(e_p^c\xrightarrow{c}e_h^c)$ denotes that e_p^c is the cause of e_h^c.

The dependency of the likelihood of causal events on use cases is presented in Table 2. The likelihood is expressed using modal logic operators (□ – stands for necessary truth, ◊ – possibility, ¬◊ – imposibility of the situation).

Table 2 – Likelihood of causal events

Trigger	Use cases relation	Entities relation	Likelihood of causal events
C(*P*)	$C(P)\xrightarrow{inc}C(H)$	<*P,H*> +	$\Box\,(e_p^c\xrightarrow{c}e_h^c)$
C(*H*)	$C(S)\xrightarrow{ext}C(H)$	<*H,S*>*	$\Diamond\,(e_h^c\xrightarrow{c}e_s^c)$
C(*H*)	$C(P)\xrightarrow{pre}C(H)$	<*P,H*> +	$\neg\Diamond\,(e_h^c\xrightarrow{c}e_p^c)$
C(*S*)	$C(H)\xrightarrow{pre}C(S)$	<*H,S*>*	$\neg\Diamond\,(e_s^c\xrightarrow{c}e_h^c)$

Considering use cases connected with modification (denoted by *M* operation) and remove (denoted by *r* predicate) types of commands (for example, the activation of account belongs to the use case of *m*-type) the following types of relations among use cases should also be analysed:

1) Relations between creation use cases connected to one entity and modification use cases connected to other entities.

2) Relations between modification use cases connected to one entity and the creation use cases connected to other entities.

3) Relations between modification use cases connected to one entity and the modification use cases connected to other entities.

4) Relations between remove use cases connected to one entity and the modification use cases connected to other entities.

5) Relations between remove use cases connected to one entity and the remove use cases connected to other entities.

On the base of several projects analysis the following results were obtained. There are two generic necessary truth rules which can be represented as follows.

The first necessary truth rule considers creation of the instances of classes connected by ≥ l[1]*r* type of relation.

Let us say *A* and *B* are the entities connected by *r*, and *C*(*A*) and *C*(*B*) are the use cases connected with the creation of their instances *a: A* and *b: B*, $C(A)\xrightarrow{inc}C(B)$ means that use case *C*(*A*) includes use case *C*(*B*), e_a^c, e_b^c are the events connected with the creation of the instances, $e_a^c\xrightarrow{c}e_b^c$ denotes that e_a^c is the cause of e_b^c, □ – stands for necessary truth. Then the first rule of the dependency between the relation of the entities, creation use cases and the corresponding causal events can be described by the logic formula as follows:

$$\textit{Iff}\ A\sqsubseteq\ \geq 1\ [1]r,\ B\sqsubseteq\ =1\ [2]r\ \textit{Then}\quad C(A)\xrightarrow{inc}C(B)\Rightarrow\Box\,(e_a^c\xrightarrow{c}e_b^c)\qquad(18)$$

Consequently

$$\textit{Iff}\ A\sqsubseteq\ \geq 1\ [1]r,\ B\sqsubseteq\ =1\ [2]r\ \ \textit{Then}\ \ \Box\,(e_a^c\xrightarrow{c}e_b^c)\qquad(19)$$

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The second necessary truth rule considers removal of the instances of classes. Independently of the first component of the relationship, if the multiplicity of the second is =1, then the remove use cases will be connected with includes relationship and cause the events causality, which can be described by the logic formula as follows
Iff B ⊑ = 1 [2]*r Then*

$$R(A) \xrightarrow{inc} R(B) \Rightarrow \Box\,(e_a^r \xrightarrow{c} e_b^r) \qquad (20)$$

$R(A) \xrightarrow{inc} R(B)$ means that use case *R*(*A*) includes use case *R*(*B*), e_a^r, e_b^r are the events connected with the removing of the instances.

The other relations between the use cases depend on the functional requirements of the system and cannot be generalized, but they could significantly affect the risk of the issue, therefore we tried to organize the information which was obtained from the realized projects using relationship matrices shown in Fig. 5 and Fig. 6.

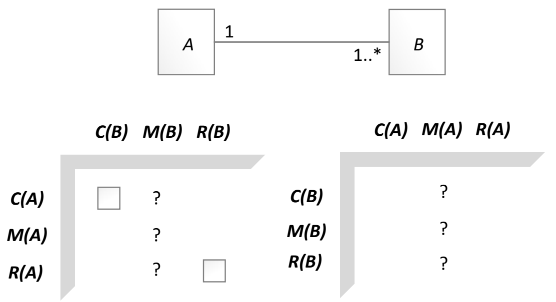

Figure 5 – Dependency of causal events on the relations between the use cases for 1–1..* relation

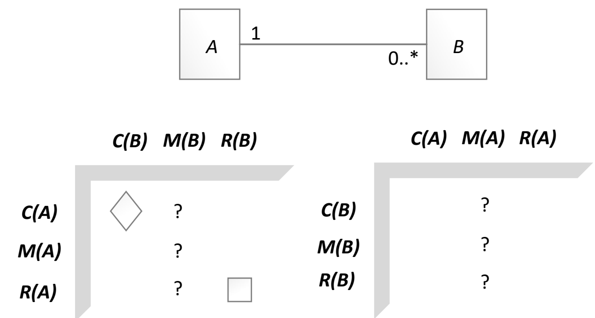

Figure 6 – Dependency of causal events between the use cases for 1–0..* relation

The left matrix shows the relations in direction from the use cases engaging *A* entity, to the use cases engaging *B* one, i.e. <$U_i(A)$, $U_j(B)$> pairs, where *B* is the aggregated entity, the right matrix shows the relationships of the use cases in opposite direction. $U_i(X)$ and $U_j(X)$ stand for one of 𝔄 use case types (the basic types are *C, M, R*), engaging *X* entity. □ – stands for necessary truth, ¬◊ – possibility, empty space means that the relation is impossible, i.e. ¬◊ necessary false. "?" – means that the likelihood is undefined because it depends on the specific of the system requirements and whilst for one subset of the existing systems under consideration it may be necessary truth, for second it may be only possible and for the third it is absolutely impossible. For example, if, in accordance with the requirements, the relation between *M*(*A*) and *M*(*B*) is "*M*(*A*) includes *M*(*B*)" then the likelihood of the causal events is necessary truth, i.e. $\Box\,(e_a^m \xrightarrow{c} e_b^m)$ etc.

Some of the presented dependencies are not trivial and connected to the certain type of the projects. For example, the relation <*C*(*A*), *C*(*B*)> (Fig. 6) is rear: it appeared in the financial system where *C*(*A*) caused the modification of several existing instances of *B* in accordance with the settings rule, which can then be aggregated by the object.

The generic use cases diagrams for two basic variants of the entities relations mentioned above are shown in Fig. 7. The dotted edges without labels denote undefined relations.

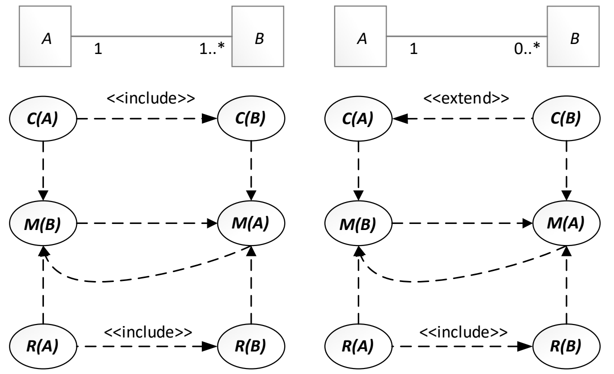

Figure 7 – Relations between basic use cases for 1–0..* and 1–1..* associations

Undefined dependencies for the certain project can be resolved using the information on the projects (ideally of the same type) which has been previously realized.

The probability of the include or extend type relation occurrence can be evaluated by the ratio of frequency of occurrence of such relation to the number of aggregation relationships within the project.

In result, we can evaluate the number of potential cases where the issue could appear, and, consequently, to choose the method of its resolution.
For example, if we have the probabilities of the include-type relation between the use cases connected with *A* and *B* entities linked by the association of 1–1..* multiplicity for a project of a certain type as it is shown in Fig. 8. Then we can guess that the number of the potential causal events for each aggregation relation with the 1–1..* for a new project of the same type will be approximately 2.9 (i.e. for 10 cases it will be 29 etc.). The same way we can evaluate the number of cases for the relation of the extend-type.

To increase the accuracy of the estimation not only projects should be classified, but also the entities and their relations should be also considered.

Of course, the evaluation cannot identify the number of critical causal events. To evaluate the potential number of critical causal events we may monitor the ratio of their

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number to the number of the inclusion and extension probabilities.

Thus, the result may be as it is shown in Fig. 9.

	C(B)	M(B)	R(B)
C(A)	1	0.1	
M(A)		0.3	
R(A)		0.1	1

	C(A)	M(A)	R(A)
C(B)		0.2	
M(B)		0.1	
R(B)		0.1	

Figure 8 – The probabilities of the include-type relation between the use cases for a project

	C(B)	M(B)	R(B)
C(A)	0.5	0	
M(A)		0.1	
R(A)		0.02	0.1

	C(A)	M(A)	R(A)
C(B)			
M(B)		0.1	
R(B)			

Figure 9 – The probabilities of the potential number of critical causal events for include-type relation between the use cases for a certain type of entities

This approach can give a more or less accurate assessment of the probability of potential critical causal events for a project if the company has already implemented similar projects using the same architecture. It should be noted that the classification of projects, entities, and maintaining statistics on projects is a labour-intensive task and cannot be implemented without automation.

In conclusion, to summarize the presented information we can define as follows. The best way to estimate the risk of critical causal events occurrence is to use the history related to the same type of projects, considering relations of 1–1..* and 0–1..* types between the entities and the derived relations among use cases. Whether the absence of the history it is very important to take into consideration the dependencies of causal events on the relations between the use cases shown in Fig. 5 and Fig. 6 and thoroughly analyse the project trying, firstly, to choose the entities linked by the relations of such type, secondly, to analyse the use cases identifying the causality of the events, and, thirdly, choosing critical causal events of them.

Depends on the likelihood of critical causal events, different solutions are favourable. Let's consider four solutions to the issue of synchronizing critical causal events in systems based on CQRS with ES architecture, along with their advantages and disadvantages.

The first variant is "New event introduction". The main idea is to create a new event that represents the composition of critical causal events.

Let us see the modifications of the system in case when the use cases connected by the "includes" association.

$$U_i(A) \xrightarrow{inc} U_j(B) \wedge U_i(A) \Rightarrow \square(E_{a+b}^{U_i}) \qquad (21)$$

In this case $U_i(A)$ triggers execution of $U_j(B)$ use case which results in generating one composed event $\square(E_{a+b}^{U_i})$ which can be linked to U_i use case (e.g. PatientWithHospitalizationCreated which contains included HospitalizationCreated event). At first glance the number of events remains the same (just PatientCreated event is substituted by PatientWithHospitalizationCreated), but the handler subscribed to $E_b^{U_j}$ type of events should be also subscribed to the events of $E_{a+b}^{U_i}$, because in case when $U_j(B)$ occurs independently of $U_i(A)$, which can happen in case of 1–1..* relation, an event of $E_b^{U_j}$ will be generated, i.e.

$$U_i(A) \xrightarrow{inc} U_j(B) \wedge U_j(B) \Rightarrow \square(E_b^{U_j}) \Rightarrow \neg\lozenge\neg E_{a+b}^{U_i}. \qquad (22)$$

In case when the use cases connected by the "extends" association the situation is as follows.

$$U_j(B) \xrightarrow{ext} U_i(A) \wedge U_i(A) \Rightarrow \square(E_{a+b}^{U_i} \vee E_a^{U_i}) \qquad (23)$$

and

$$U_j(B) \xrightarrow{ext} U_i(A) \wedge U_j(B) \Rightarrow \square(E_b^{U_j}). \qquad (24)$$

Thus, three events should be introduced and all $E_b^{U_j}$ and $E_a^{U_i}$ handlers should be also subscribed to $E_{a+b}^{U_i}$ event.

The situation becomes worse when we have the following relation of the use cases (Fig. 10).

In this case $U_i(A)$ can result four different types of events.

$$\left[U_j(B) \xrightarrow{ext} U_i(A) \wedge U_k(C) \xrightarrow{ext} U_i(A)\right] \wedge U_i(A) \Rightarrow \square(E_{a+b+c}^{U_i} \vee E_{a+b}^{U_i} \vee E_{a+c}^{U_i} \vee E_a^{U_i}). \qquad (25)$$

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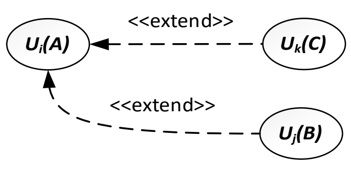

Figure 10 – Multiple extend relation example

$E_a^{U_i}$ handler should be subscribed to and consider handling of $E_{a+b+c}^{U_i}, E_{a+b}^{U_i}, E_{a+c}^{U_i}$ types of events.

$E_{a+b}^{U_i}, E_{a+c}^{U_i}$ handlers should consider $E_{a+b+c}^{U_i}$.

$E_b^{U_j}$ handler to $E_{a+b+c}^{U_i}, E_{a+b}^{U_i}$.

$E_c^{U_k}$ handler to $E_{a+b+c}^{U_i}, E_{a+c}^{U_i}$.

For example, there is HospitalizationCreated event created as a result of processing the command. It can optionally cause the creation of surgery and diagnostic procedures. Such case can lead to creation of three composite events:

– HospitalizationWithSurgeryAndDiagnosticCreated;
– HospitalizationWithSurgeryCreated;
– HospitalizationWithDiagnosticCreated.

HospitalizationCreatedHandler should probably need the subscription to all three of them, HospitalizationWithSurgeryCreatedHandler and HospitalizationWithDiagnosticCreatedHandler potentially need the subscription to HospitalizationWithSurgeryAndDiagnosticCreated. SurgeryCreatedHandler and DiagnosticCreatedHandler both need subscription to HospitalizationWithSurgeryAndDiagnosticCreated as well as HospitalizationWithSurgeryCreated and HospitalizationWithDiagnosticCreated respectively. So, using this synchronization method with such a relationship can generate 8 additional subscriptions for existing handlers to new events, increasing code complexity and deteriorate code readability.

Now, let's imagine that there are 10 occurrences of such three use cases relations. It results in introduction 30 extra events, and 80 new subscriptions, as well as extra work related to updating the handlers. Thus, the provided solution can lead to an increase in code complexity and often results in code duplication [51].

Of course, here is presented the worst-case scenario. If the *a* + *b* and *a* + *c* combinations of events are not critical, these types of events can be ignored and only one *a* + *b* + *c* extra type of events must be added.

The second variant of the problem's solution is based on using synchronous event queues instead of a classical event bus variant [52, 53]. It solves the issue by ordering the handling of events, but it may cause performance issues.

The third variant is the variation of Causal Barrier method [28] [38], the main idea of which is to provide partial history of causality considering the bounded lifetime Δ for the events-messages [34]. This method is effective when the number of causal events in the history can be high, which can negatively affect the performance of the event-driven system. The other assumption connected to that method is that handling of the events may not require full history of causality. But for the systems under consideration the history of causal events does not exceed 3–4 events and dividing the history into chunks results in handlers' complication and decreasing the usability of API (when the handlers are the third-party services). The cases of handling events by the subscribers using only partial history are the exception rather than the rule. As it is mentioned in [19], to maintain the causal order of events, a site must verify that all events within the causal history of the received event have been handled before processing it.

The complexity of the modification can be expressed in terms of the number of scenarios that the client needs to handle depending on the number of causal events within the *Ej* group.

The modifications that should be applied to each handler for two causal events are shown in Fig. 11.

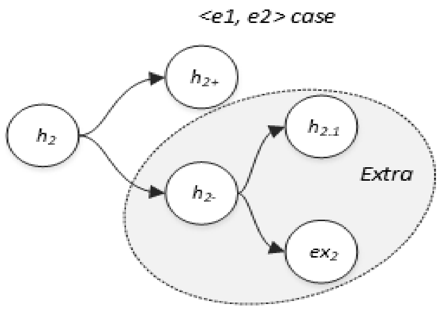

Figure 11 – The modifications must be applied according to the Causal Barrier approach to process two causal events

For the case of two causal events the following notation is used:

$< e_1, e_2 >$ – an ordered set of causal events, where $e_1 < e_2$ ("<" means the strict partial order relation).

h_{2+} – basic-positive part of the handler responsible for processing E_z according to the scenario when the events come in proper order i.e. $< e_1, e_2 >, e_1 : E_1, e_2 : E_2$. This part cannot be omitted and can be regarded as a minimal part of the handler needed to process a e_2 event.

h_{2-} – alternative-negative part of the handler responsible for processing the following situations:

$h_{2.1}$ – when the order of events $< e_2, e_1 >$ instead of $< e_1, e_2 >$;

ex_2 – an exceptional situation when e_2 is lost or can be considered as lost after a defined period of time, i.e. bounded lifetime Δ has expired.

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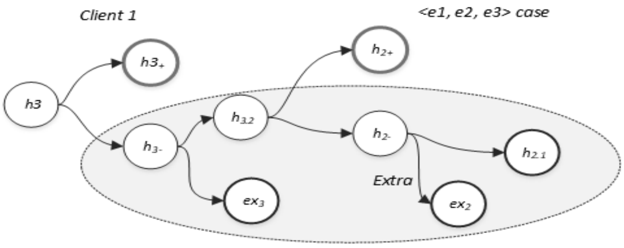

Figure 12 – The modifications must be applied according to the Causal Barrier approach to process three causal events

The three causal events case (Fig. 12) looks much more complicated. The case h_{2-} should be considered, when e_2 has come but e_1 has not come yet, and e_2 is in the state of waiting for confirmation. It is notable that the current description doesn't touch the part responsible for exception handling which can be realized in different ways.

Thus, the number of scenarios that the client needs to handle (the complexity of the modification) depending on the number of connected events within the *Ej* group can be evaluated using the formula (26).

$$|C(Ej)| = 2 * k - 1. \quad (26)$$

Let us see the variant of client modification in the example for the sequence of events <PatientCreated, HospitalizationCreated>.

The first scenario is when the sequence of events is received by the client application in the order as it was sent, e.g. in the proper order. In this case, the events are processed sequentially (see Fig. 13).

The second scenario involves a situation where the HospitalizationCreated notification arrives first. In this case, after receiving the HospitalizationCreated notification and determining that the patient to which the hospitalization belongs does not exist, the client waits for a PatientCreated event for a specified period. Upon receiving the PatientCreated notification, both notifications are processed together (see Fig. 14).

In the last scenario, if the PatientCreated notification does not arrive within the specified waiting time, the Client logs an error and/or requests a full initial context from the server (see Fig. 15).

This solution solves the problem, but it significantly complicates the construction of the client, negatively affecting the usability of the system's API, i.e. each client such as different mobile and desktop applications, including other services should be prepared to handle these cases.

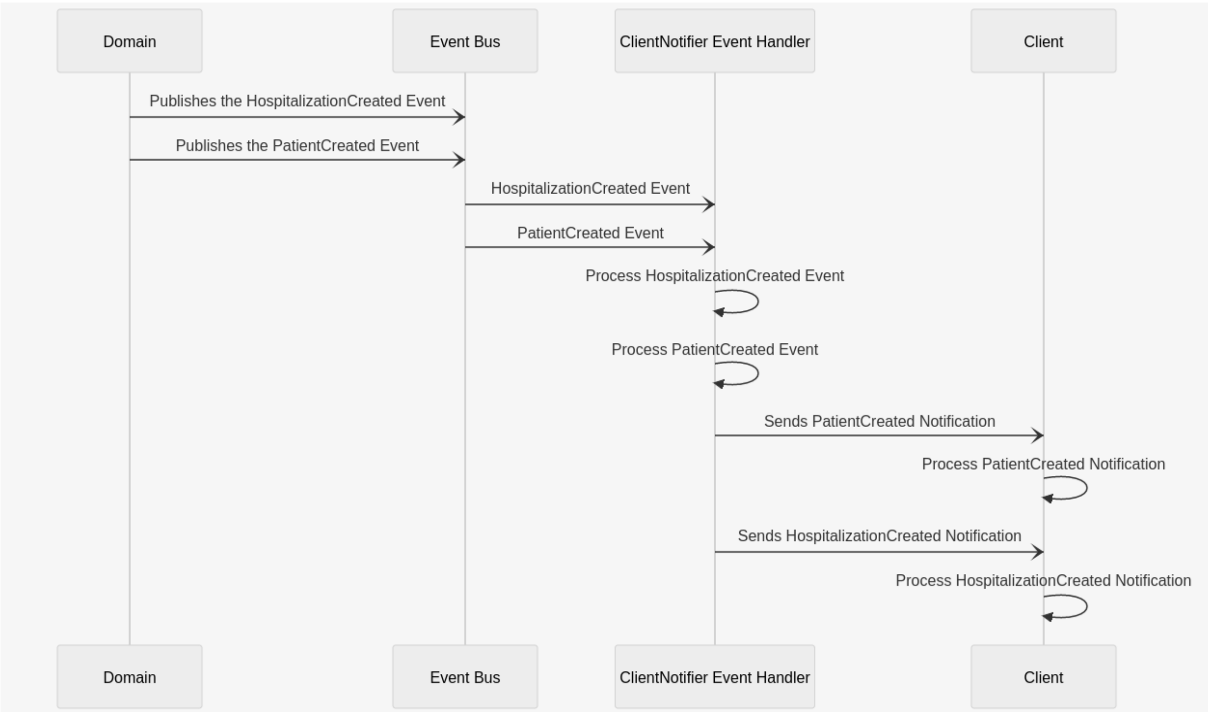

Figure 13 – The basic scenario of events processing using the Causal Barrier approach. The case when the PatientCreated event is received before HospitalizationCreated

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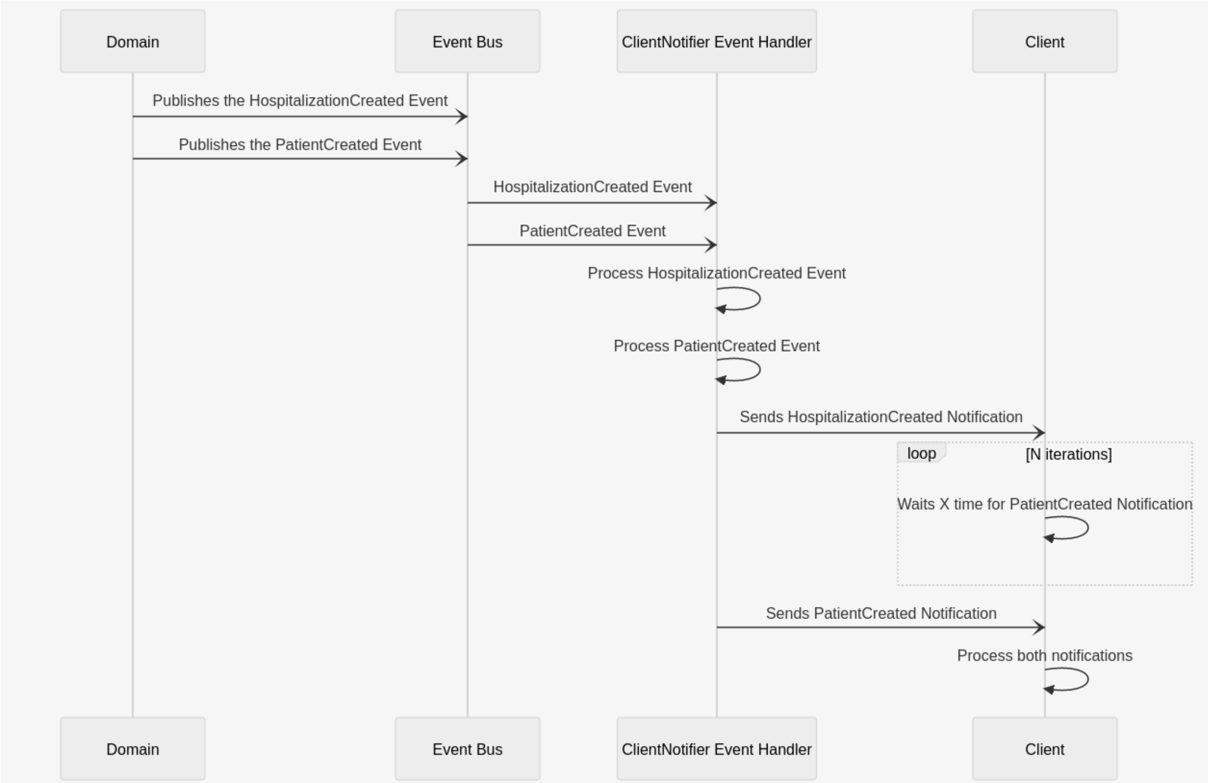

Figure 14 – The basic scenario of events processing using the Causal Barrier approach. The case when the PatientCreated event is received after HospitalizationCreated

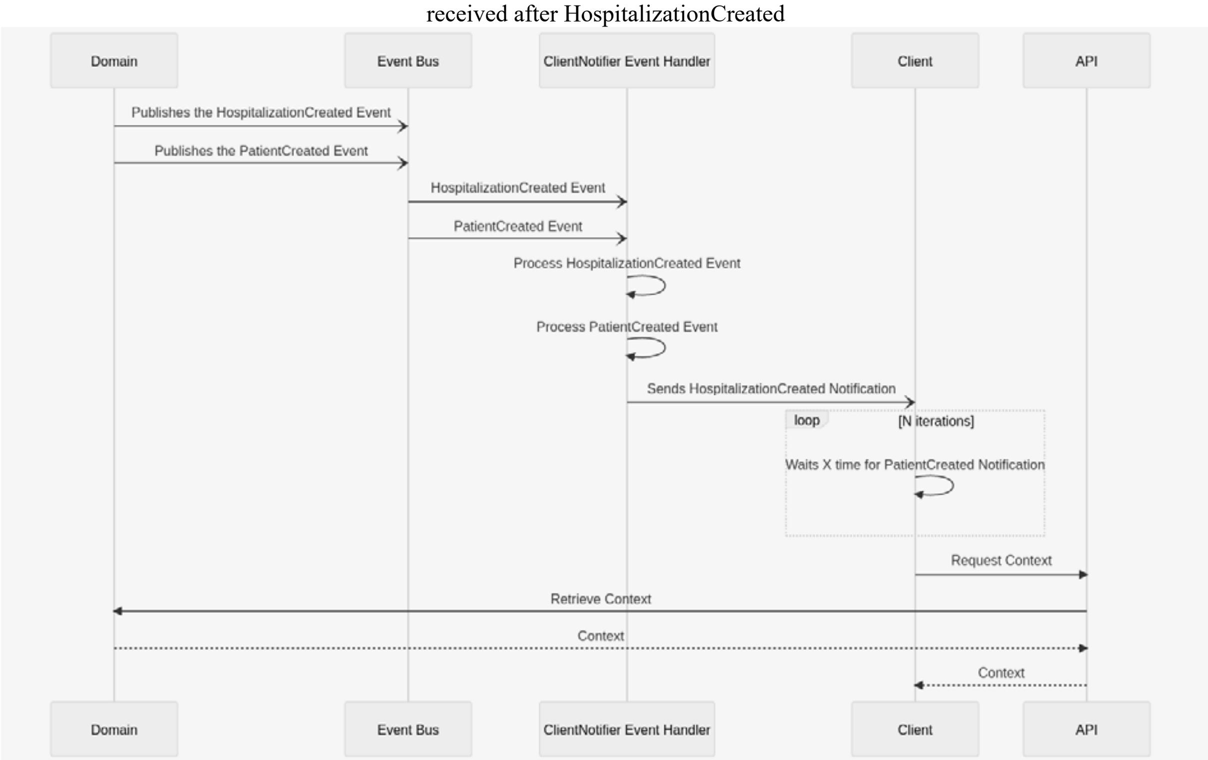

Figure 15 – The basic scenario of events processing using the Causal Barrier approach. The case when the PatientCreated event is not received

The last variant of the solution is based on presenting of full history of causality. The variation proposed in this paper differs from the classical solutions (e.g. [37]) in that it is more flexible and more effective for CQRS with ES architecture.

The solution is based on introduction of an abstract container of events that can be used for delivering the

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causal events. It can be called a complex event or a Container of Events (Code snippet 1).

There are three basic ways of event publishing unit modifications in order to deliver event containers. The first one which is based on Event Bus modification is as follows.

For each container, Event Bus (i.e. event publishing unit) analyses its content and if some handler is subscribed to one or more events from the group, it delivers these events in proper order to that handler. This variant requires spending more effort to modify the event publishing unit, but it does not touch the handlers.

The second variant, which is the opposite variant to the first one, is to deliver all event containers to all the event handlers (a variant of broadcast notification) making the handlers responsible for analysing the content of containers and choosing the right method to process the events. This variant requires the introduction of an abstract handler able to get the events from the container and choose the proper method/methods of their processing. The advantage of the solution is avoiding Event Bus modification.

The third variant is the composition of the first and the second. Instead of doing container of events broadcasting, Event Bus sends the event containers only to the event handlers subscribed to one or more events from the group, using a generic method. In this case, the event handler is responsible for analysing the payload, defining the order of events publishing, and choosing the proper method/methods to process the events. This variant seems to be the most effective solution, because of reducing the number of handlers to notify, but it requires a slight modification of the Event Bus.

At the implementation level, for the third variant, two following approaches should be considered. The first one involves creating a container event handler within the base class, which unpacks the container of events and then invokes the appropriate methods of the derived classes, passing subgroups of events from the container. This approach is based on defining method signatures, using reflection mechanisms. It does not require any modifications to the handle methods of the derived classes and proves effective when integrating Container of Events solutions into a system that already has a large number of handlers. The second approach entails defining in the base class only the function for unpacking the container of events, which is then utilized in the handle methods of the subclasses. After unpacking, these methods process events in the defined order. This solution is more flexible, as it allows adding additional logic for handling events section of handle methods of each handler.

The complexity of this solution is independent of the number of causal events within the *Ej* group. All the necessary changes are made to the system's infrastructure, and it plays a crucial role in assessing the ease of implementing future changes in the system across observable solutions.

To reduce resource costs when implementing new handlers, a base handler with an implementation of the UnpackContainer function is created (Code snippet 2) All handlers processing causal events inherit from the BaseHandler (Fig. 16). Upon receiving the event container, the handler unpacks it and processes the events synchronously (Code snippet 3).

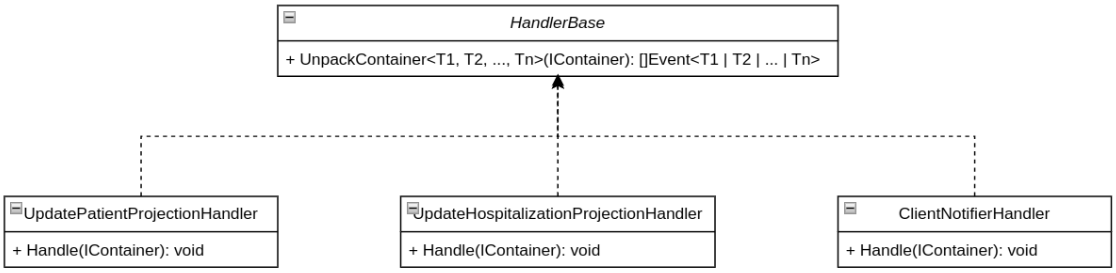

Figure 16 – The variant of solution based on the introduction of the BaseHandler.

Code snippet 1

```
{
    Title: string,
    Events: [
        {
            header: string,
            body:   JSON string
        }
    ]
}
```


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Code snippet 2

```
class HandlerBase {
  UnpackContainer<T1, T2, ..., Tn>(container: IContainer): []Event<T1 | T2 | ... | Tn> {
                events: []Event<T1 | T2 | ... | Tn> = []
                For container.Events (event: Event) {
                        if ([T1, T2, ..., Tn].includes.(event.type) {
                                events.Add(events)
                        }
                }
                return events
        }
}
```

Code snippet 3

```
class Handler inherits HandlerBase {
        Handle(container: IContainer): void {
                events = self.UnpackContainer<_handledTypes>(container)
                For events (event: Event<_handledTypes>) {
                        Process event synchronously
                }
        }
}
```

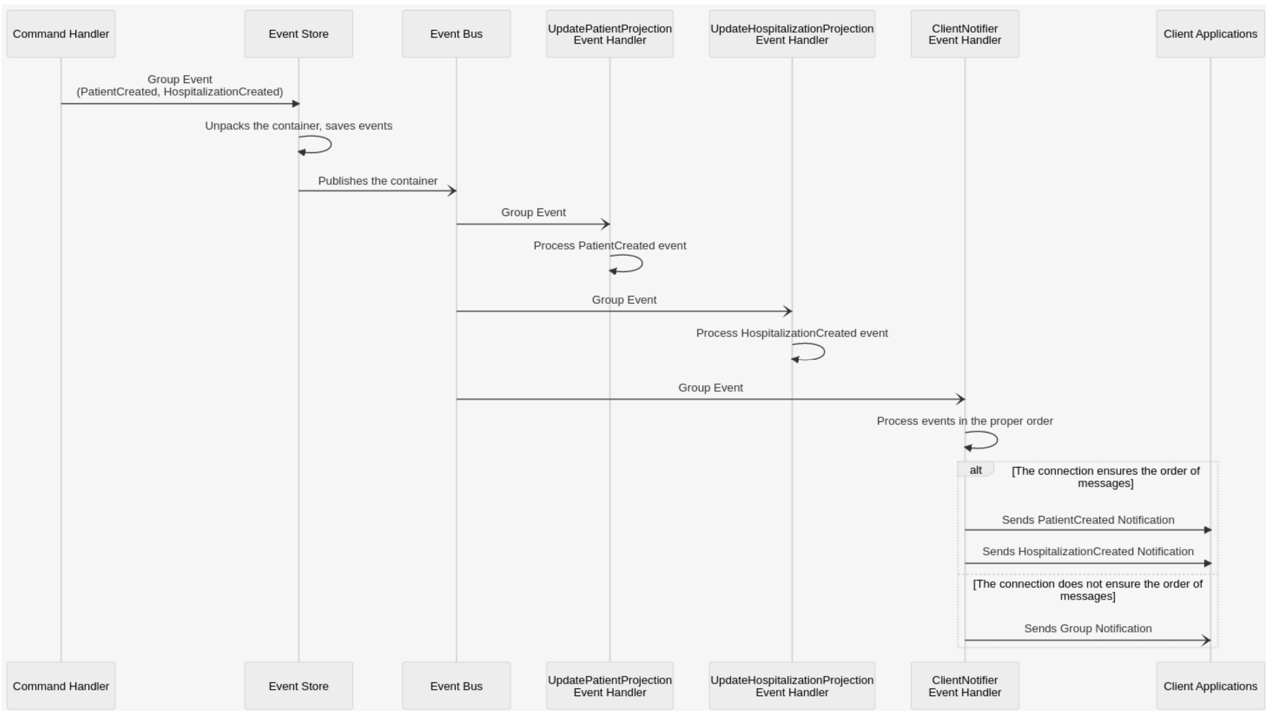

Figure 17 – The basic scenario of events processing according to the Container of Events approach

For the above example, it works as follows. For the hospitalization creation task, the command handler puts the sequence of generated events into a container with the title “HospitalizationCreation” (<PatientCreated, HospitalizationCreated>). Then it passes the container to the Event Store which unpacks the container, saves events, and publishes the container. Then the event handlers subscribed to the PatientCreated or HospitalizationCreated events receive the container. In our case UpdatePatientProjection handler is subscribed to PatientCreated event, UpdateHospitalizationProjection – to HospitalizationCreated event and ClientNotifier handler – to both of them. So all these handlers will receive the container, unpack that container and process the events in proper order which is <PatientCreated, HospitalizationCreated> (see Fig. 17). After processing

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the Container of Events by Notification handler, the Notifications are sent to the Client Application. If the connection between the Notification Service and the Client Application guarantees that the order of delivery is preserved, the service sends notifications one by one in the correct order (e.g. WebSockets guarantees the preservation of the delivery order [54]). Otherwise, the Notification Service builds a notification, that includes information from container of events, and sends it to the client application as a single message. In that case, the client application should be adapted for notifications handling making the client application able to transform the Container of Events into a sequence of events calling them one by one in the correct order.

4 EXPERIMENTS

The strategy chosen to conduct the experiment is as follows.

The typical test application to realize the tasks described in part 3 was created and published to GitHub [55]. Initially, the system domain contained only two causal events that were processed asynchronously. The four solutions proposed above were realized concurrently and published to different Git branches.

The first phase of the experiment involves evaluating the complexity of the code required for integrating each of the four modifications.

In the second phase of the experiment two additional causal events were added to the domain of the system, and these changes were merged into each version with the integrated methods for solving the causal events synchronization issue. Then, after merging, the versions were updated to be operational and the complexity of code changes for the update was evaluated for each method.

The third phase of the experiment involves evaluating the performance of each of the integrated methods.

The fourth phase can be considered as calculating the complexity-performance comparative assessment of the considered methods.

Several methods for assessing the complexity of task implementation were considered [56][57]:

Lines of Code [57]. The approach suggests that the complexity of a software product is directly dependent on the number of lines of code in the product. It’s a simple but not very accurate and relevant estimation.

The Number of Statements Metrics [56] serves as an indicator of the quantity of statements within a method. On the positive side, the Number of Statements Metrics offers a nuanced measure of method complexity, providing a more stable evaluation compared to Lines of Code. It encourages the identification of logical groupings within a method, fostering improved code organization. However, a potential drawback lies in its reliance on the subjective process of method extraction, which could introduce variability in interpretation.

Object Points [57] is a metric method that assigns weights to software modules. While it can be described, the process of assigning weights may lack clarity, and it does not inherently consider the uniqueness of the code. This metric primarily serves estimation purposes rather than evaluating the finalized code.

Information flow complexity [58]. The method entails evaluating information flow complexity in a software system through the analysis of function call quantity, frequency of invocation, and the number of functions each function calls. Its robustness lies in offering a holistic perspective on the data and control flow within the system, facilitating the identification of dependencies and potential bottlenecks. This approach is especially valuable for assessing and managing the complexity of software codebases characterized by considerable function nesting.

Cognitive functional size [59]. The Cognitive Functional Size (CFS) approach involves quantifying the functional size of software based on the cognitive load required for developers to comprehend and interact with the system. Notably, it excels in providing a user-centric measurement, capturing the complexity from the perspective of understanding and processing functionality. This method is particularly valuable for comparing the complexity of entities, such as classes, offering a more insightful evaluation that aligns with the cognitive demands placed on developers interacting with those entities.

Dep-degree metrics [60]. The approach operates on the principle that a program becomes more challenging to understand as the programmer’s short-term memory is burdened with more chunks to remember. The DepDegree is a method of the cumulative count of dependencies for its statements, aligning with the psychological understanding that immediate memory has a limited capacity.

McCabe’s cyclomatic complexity [61]. The complexity measurement is based on the amount and level of functions, methods, and procedures (e.g. loops and conditions). The higher this amount, the more difficult it will be for the developer to build, understand, and modify the code. This method excels most when evaluating complex algorithms. For simple operations, it may not provide high accuracy and may not reveal the true variability in the complexity of implementation.

Halstead Software Science Metrics (HSSM) [62]. These metrics are used to quantify the complexity of software by analysing the composition of code within program modules. The approach calculates three primary complexity metrics of a program: volume (V), difficulty (D), and an effort (E). The formula for calculating the effort in Halstead Software Science Metrics is as follows:

$$E = D * V. \quad (27)$$

V represents the program’s volume, which is calculated using formula 28. D represents the program’s difficulty, which is computed using formula 29.

$$V = (N_1 + N_2) * \log_2(n_1 + n_2). \quad (28)$$

$$D = (n_1 / 2) * (N_2 / n_2). \quad (29)$$

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The Halstead Software Science Metrics is a straightforward method for measuring code complexity that performs well in assessing the intricacy of simple code. It takes into consideration both the volume of code and its uniqueness. The main cons of the method are ignoring the higher-level software design and architectural considerations and limited scope. Halstead Metrics primarily focuses on the code itself and may not provide a comprehensive view of software code quality, performance, or other important factors.

Another critical metric in such systems, besides complexity and the effort required to implement a solution, is performance. The performance metric was determined by measuring the time taken, experimentally, from the submission of a data change request to the data update on the Client side.

To provide an overview and highlight the pros and cons of each approach, three different measurements were conducted:

– Average update time when sending 100 data update requests with a 10-millisecond interval.

– Average update time when sending 1000 data update requests with a 10-millisecond interval.

– Average update time when sending 100 parallel data update requests, repeated 100 times with a 200-milliseconds interval.

For a more accurate assessment, the experiment was repeated three times using machines with different technical specifications. The final evaluation is the arithmetic mean of the three obtained measurements. It is also worth noting that a relatively simple implementation of the considered solution methods was provided for the experiment. For example, for the variant with a queue, the in-memory queue "Sync-Queue" [63] was used; using other tools such as AWS SQS [64] or Apache Kafka [65] would yield different assessment results.

To compare this metric across multiple solutions, a specific system runtime metric was measured for each solution multiple times and the average value was calculated. Thus, this average value is a percentage relative to the maximum performance solution variant (formula 30).

$$P_k = \frac{T_{\min}}{T_k}. \qquad (30)$$

To make the complexity-performance comparative assessment of the considered methods more descriptive, formula 31 is derived. When using this formula, the effort expended on integrating the solution (C_i) is considered equally important to the effort expended on the system's maintenance (C_m) with the integrated solution. Therefore, the coefficients α and β are set to 0.5. In other situations, the coefficient selection may involve using the Rank Correlation method [66]. Since the comparison is conducted within the scope of a single system, the significance of performance relative to implementation complexity can be disregarded, and the coefficient ρ = 1.

$$E_{\text{int}} = \rho * \frac{P_{avg}}{\alpha * C_i + \beta * C_m} * 10^l. \qquad (31)$$

The effort for integration (C_i) is calculated using the Halstead Software Science Metrics method in Phase 1 of the experiment. The effort required for system's maintenance (C_m) calculated in Phase 2 of the experiment. For the average relative performance (P_{avg}) the arithmetic mean is taken among the three metrics obtained during the third phase of the experiment (formula 32).

$$P_{avg} = \frac{P_{ll} + P_{hl} + P_{hpl}}{3}. \qquad (32)$$

Given that the relative performance is a percentage metric, and the effort calculated using the Halstead Software Science Metrics method has the order of four, let us assume the order of magnitude coefficient (l) to be 3.

5 RESULTS

Phase 1. The Halstead Software Science Metric provides a reasonably accurate reflection of the time spent on implementing each solution variant. The code of each solution was analysed and the number of distinct operators and operands (Distinct operators, Distinct operands, Occurrences of operators, and Occurrences of operands) were obtained. The metrics required for each variant implementation (Volume, Difficulty, and Effort) were calculated by formulas 27–29. The results of the calculation are represented in Table 3 and visualized in charts (Figs. 18–20).

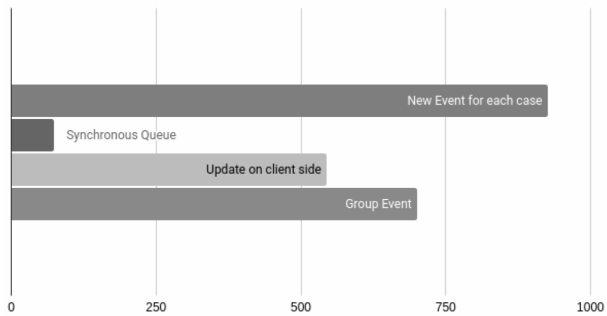

Figure 18 – Program Volume. Phase 1

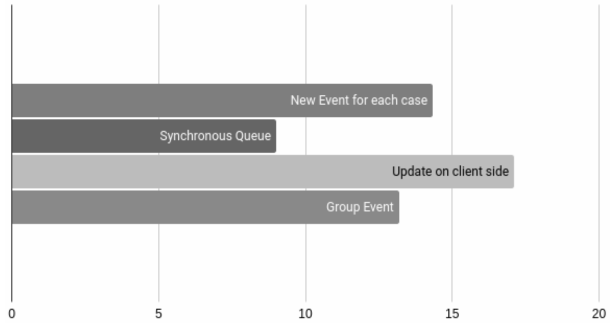

Figure 19 – Program Difficulty. Phase 1

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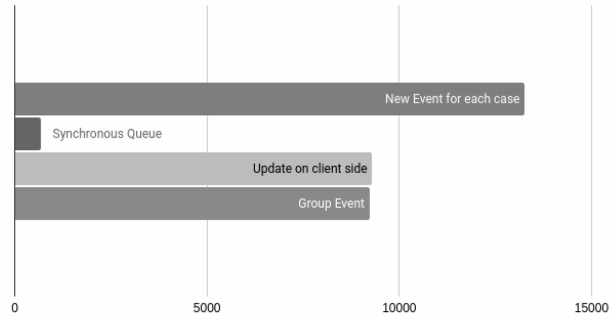

Figure 20 – Programming Effort. Phase 1

Phase 2. The second phase of the experiment was conducted to assess the additional efforts required for adding new pair of critical causal events to the system. I.e. the provided solution is already implemented, and new causal events are introduced. Similar to the previous phase of the experiment metrics are calculated and represented in Table 4 and Fig. 21.

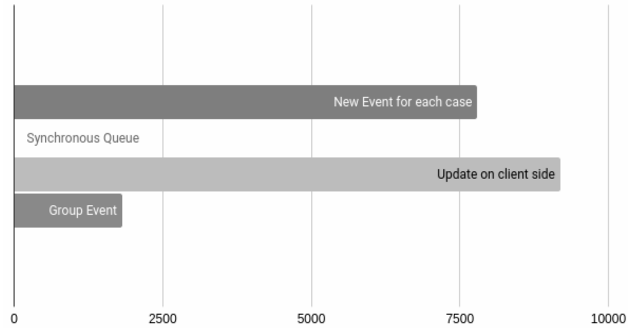

Figure 21 – Programming Effort. Phase 2

Table 3 – Complexity metrics calculated for each method. Phase 1

Metric \ Approach	Variant 1 (New event introduction)	Varian 2 (Synchronous Queue)	Variant 3 (Causal Barrier)	Variant 4 (Container of Events)
Distinct operators	18	9	16	17
Distinct operands	55	4	29	40
Occurrences of operators	64	12	37	58
Occurrences of operands	86	8	62	62
Program Length	150	20	99	120
Halstead Vocabulary	72	13	45	57
Program Volume	925.49	74.01	543.69	699.95
Program Difficulty	14.33	9	17.1	13.18
Programming Effort	13262.27	666.09	9297.1	9225.34

Table 4 – Complexity metrics calculated for each method. Phase 2

Metric \ Approach	Variant 1 (New event introduction)	Varian 2 (Synchronous Queue)	Variant 3 (Causal Barrier)	Variant 4 (Container of Events)
Distinct operators	13	0	16	9
Distinct operands	48	0	30	19
Occurrences of operators	49	0	36	26
Occurrences of operands	77	0	63	29
Program Length	126	0	99	55
Halstead Vocabulary	61	0	46	28
Program Volume	747.27	0	546.83	264.4
Program Difficulty	10.43	0	16.8	6.87
Programming Effort	7794.03	0	9186.74	1816.43

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Phase 3. For reasons of clarity, testing was conducted with the simplest possible command to minimize command validation time and aggregate state updates. Additionally, the time required for creating an aggregate was minimized through caching.

Table 5 contains average time metrics from several experiments repeated on three different computers. The chart in Fig. 22 represents the ratio of each approach metric to the fastest one in the category (which is Variant 1 – New event introduction) calculated by formula 30, that can roughly show the performance comparison of these solutions.

Phase 4. Table 6 contains the Integrated Performance-Complexity evaluation results for considered methods, calculated using formulas 31 and 32.

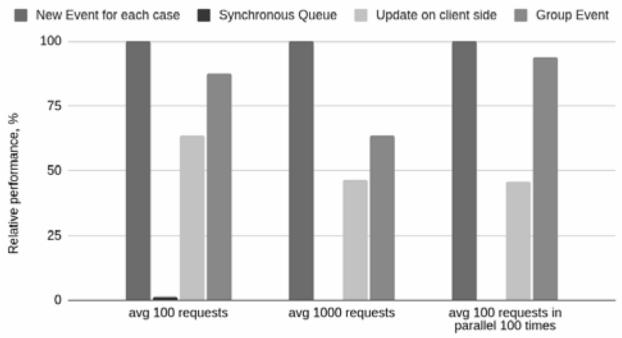

Figure 22 – Relative performance. Phase 3

Table 5 – Performance metrics calculated for each method. Phase 3

Approach \ Metric	avg 100 requests (ms)	avg 1000 requests (ms)	avg 100 requests in parallel 100 times (ms)
Variant 1 (New event introduction)	7	7	138
Variant 2 (Synchronous Queue)	453	4187	96117
Variant 3 (Causal Barrier)	11	15	301
Variant 4 (Container of Events)	8	11	147

Table 6 – Integrated Performance-Complexity evaluation. Phase 4

Metric \ Approach	Variant 1 (New event introduction)	Varian 2 (Synchronous Queue)	Variant 3 (Causal Barrier)	Variant 4 (Container of Events)
Average performance	100	0.62	52.05	81.67
Integration complexity	13262.27	666.09	9297.1	9225.34
Maintenance complexity	7794.03	0	9186.74	1816.43
Evaluation	9.49	1.86	5.63	14.79

6 DISCUSSION

According to the results presented in Table 3 the solution involving the synchronous queue (Variant 2) requires minimal Programming Effort (666.09).

The most challenging aspect is Causal Barrier solution (Variant 3). The volume of added code (543.69) is larger than that of adding for the synchronous queue variant (74.01), and the task itself proves considerably more complex (17.1 against 9) and demands more development and testing effort (9297.1 against 666.09).

The “New event introduction” (Variant 1) approach can be regarded as the simplest to implement, but due to the amount of routine work this approach is time-consuming. It can be used only for the systems with low degree of probability of casual events. It should also be noted that as the domain of the application gets more complex (i.e. new aggregates, functions, and causal events are introduced), this approach would lead to naming complexity causing the problems with maintainability of the application.

As it can be seen the Variant 4 (Container of Events) is in the second place in terms of effort (9225.34) and difficulty (13.18), following the synchronous queue solution (Variant 2. Difficulty: 9, Effort: 666.09). The effort invested in the Container of Events method (Variant 4. 9225.34) implementation is nearly identical to that of Causal Barrier (Variant 3. 9297.1). However, the “New event introduction” method requires more development effort due to the amount of routine work (Variant 1 13262.27). It also takes the third place in terms of volume (699.95), following the solutions with a queue (Variant 2. 74.01) and “Causal Barrier” (Variant 3. 543.69). The first phase of the experiment includes just a simple case for two causal events. In the case of more events, the volume of the “Causal Barrier” approach remains stable, while the volume for the “Container of Events” approach decreases.

In accordance with the results presented in Table 4, for the “Causal Barrier” approach (Variant 3), the program effort remained almost unchanged in comparison

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to the effort spent on Phase 1 (9297.1 vs 9186.74). For the “New event introduction” approach (Variant 1), the difficulty decreased due to fewer changes but remained relatively high (14.33 vs 10.43). Meanwhile, for Variants 2 and 4, the program effort significantly decreased in comparison with Phase 1. It can be explained by the fact that the main part of the code changes is applied to the infrastructure and the implementation complexity is almost independent of the number of causal events. For example, the “Container of Events” method (Variant 4) only requires routine updates to event handlers, while the “Synchronous Queue” implementation (Variant 2) used in the experiment does not require any additional changes at all.

The best performance was demonstrated by the “New event introduction” method (Variant 1). This is because this solution does not introduce any new logic into the system’s workings. However, as previously described, frequent use of this approach can lead to significant code duplication and the expansion of a list of narrowly focused events.

As expected, the solution with a synchronous queue (Variant 2) turned out to be the slowest. The performance drawbacks are especially evident when sending a large number of commands in parallel (average: 96 seconds).

The performance of the Container of Events method (Variant 4) takes the second place, trailing slightly behind Variant 1. Causal Barrier approach (Variant 3) ranks third. For tests with 100 and 1000 consecutive requests, it performs slightly slower. However, under parallel load, the difference becomes twofold. In the context of our experiment, this is explained by the inability to scale the client (browser); for clients with “server” type, such a test should yield better results.

Thus, the following conclusion can be drawn:

– If the assessment shows that the likelihood of critical causal events is low, it is better to use the “New event introduction” method, taking into account its drawbacks.

– If the assessment indicates that the likelihood of critical causal events is high, it is preferable to use either the “Synchronous Queue” method (if the system will not be under heavy load) or the “Container of Events” method.

– If predicting the likelihood of critical causal events is challenging and the system may evolve, according to the integrated comparative assessment calculations for specific systems and conditions, the “Container of Events” method (Variant 4) can be considered as the most favourable with the score of 14.79 against 9.49 for the “New event introduction” solution, which takes second place.

The use of the “Synchronous Queue” solution (Variant 2) shows poor performance, making it a situational approach that doesn’t align with our specific use cases. When comparing “Container of Events” (Variant 4) with the others, the program effort of implementing this approach is lower than the complexity of “Causal Barrier” (Variant 3) and the “New event introduction” approach (Variant 1). Nevertheless, just plain adding of new events for each case (Variant 1) works slightly faster. Across performance-appropriate solutions, the “Container of Events” solution effectively addresses the issue with the lowest development effort for implementation and maintenance. It is worth noting it helps to avoid code duplication.

CONCLUSIONS

The scientific novelty. For the first time the method of estimation of the likelihood of causal events occurring within the systems based on CQRS and ES architecture and its formal description are suggested. The method is based on analysis of entities, their interconnection and the analysis of use cases connected to the entities and their relationships. The variant of precise prediction of the critical causal events occurrence based on the history of existed solutions has been also provided.

The “Container of Events” method is firstly proposed to solve the problem of critical causal-events for system based on CQRS with ES architecture. It effectively addresses the issue for most of the researched systems with the lowest development effort for implementation (HSSM Effort: 9225.34) and maintenance (HSSM Effort: 1816.43) across performance-appropriate solutions and without code duplication. The method of Integrated Performance-Complexity evaluation which helps to make complexity-performance comparative assessment more descriptive is firstly proposed. Evaluation based on this method are 14.79 for the “Container of Events” method against 9.49 for the “New event introduction” solution, which takes second place.

Commonly used synchronization methods such as Variant 1 (New event introduction), Variant 2 (Synchronous Queue), and Variant 3 (Causal Barrier) are formalized and assessed.

The practical significance of the obtained results is as follows. The formalized and assessed methods can be used for effective real information systems development. The strategy of experiment conducting applied to assess the complexity of the modification can be used in practice to resolve similar tasks (e.g. conducting similar experiments). The proposed indicators and methods can be used to determine effective conditions for the experiments connected with the complexity and performance evaluation.

The proposed solution which is provided to the systems based on CQRS with ES Architecture can also be applied to other systems in which the sequential delivery of events is not guaranteed.

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The experiment was conducted on the DBB Software company’s [43] proprietary platform, which provided the necessary infrastructure and tools for data collection and analysis. This platform offered essential capabilities for our research, ensuring the accuracy and reliability of our experimental results.

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КРИТИЧНІ ПРИЧИННО-НАСЛІДКОВІ ПОДІЇ В СИСТЕМАХ ЗАСНОВАНИХ НА ОСНОВІ АРХІТЕКТУРИ CQRS З EVENT SOURCING

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АНОТАЦІЯ

Актуальність. У статті розглядається проблема асинхронності причинно-наслідкових подій, що виникає в сервісно-орієнтованих інформаційних системах, які не гарантують доставку подій у порядку їх публікації. Це може призвести до помилок, які виникають випадково, як правило нерегулярно, у системі, яка протягом основного часу функціонує без збоїв.

Мета роботи. Метою роботи є порівняння та оцінка кількох існуючих підходів та пропонування нового підходу до вирішення проблеми синхронізації причинно-наслідкових подій у системах, які побудовані з застосуванням архітектури Command Query Responsibility Segregation (CQRS) з Event Sourcing (ES).

Методи. По-перше, пропонується метод оцінки ймовірності виникнення причинно-наслідкових подій у системах, як основа для вибору рішення. Так, на основі результатів аналізу кількох проектів, побудованих з застосуванням архітектури CQRS з ES, показано, що ймовірність критичних причинно-наслідкових подій залежить від взаємозв'язків між сутностями та юз-кейсів, пов'язаних із сутностями. По-друге, у цій роботі пропонується метод "Container of events", який представляє варіацію події з

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повною історією причинно-наслідкових зв'язків, адаптовану до потреб систем побудованих з застосуванням архітектури CQRS з ES. Також обговорено варіанти його практичного впровадження. Крім того, були формалізовані та оцінені різні рішення, такі як синхронні черги подій та варіація методу "Causal Barrier". По-третє, представлені методи, були описані та оцінені за критеріями продуктивності та складності модифікації. Для отримання порівняльної оцінки складності та продуктивності була вперше запропонована інтегрована формула оцінки.

Результати. Результати оцінки показують, що найефективнішим рішенням проблеми є використання методу "Container of events". Для впровадження рішення необхідно внести зміни до підсистеми доставки подій та інфраструктури обробки подій.

Висновки. Робота зосереджена на вирішенні проблеми критичних причинно-наслідкових подій для систем, побудованих з застосуванням архітектури CQRS з ES. Запропоновано метод оцінки ймовірності виникнення критичних причинно-наслідкових подій, а також формалізовано та оцінено різні рішення цієї проблеми. Було запропоновано найефективніше рішення на основі методу "Container of events".

КЛЮЧОВІ СЛОВА: Сервісно-Орієнтована Архітектура, Архітектура, заснована на подіях, Event sourcing, Синхронізація подій, Проектування на основі домену.

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ESTIMATION OF FORMANT INFORMATION USING AUTOCORRELATION FUNCTION OF VOICE SIGNAL

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ABSTRACT

Context. The current scientific problem of extracting biometric characteristics of a user of a voice authentication system, which can significantly increase its reliability, is considered. There has been performed estimation of formant information from the voice signal, which is a part of the user template in the voice authentication system and is widely used in the processing of speech signals in other applications, including in the presence of interfering noise components. The work is distinguished by the investigation of a polyharmonic signal.

Objective. The purpose of the work is to develop procedures for generating formant information based on the results of calculating the autocorrelation function of the analyzed fragment of the voice signal and their subsequent spectral analysis.

Method. The procedures for generating formant information in the process of digital processing of voice signal are proposed. Initially, the autocorrelation function of the analyzed fragment of the voice signal is calculated. Based on the results of the autocorrelation function estimation, the amplitude-frequency spectrum is calculated, from which the formant information is extracted, for example, by means of threshold processing. When the signal-to-noise ratio of the analyzed voice signal fragment is low, it is advisable to iteratively calculate the autocorrelation function. The latter allows increasing the signal-to-noise ratio and the efficiency of formant information extraction. However, each subsequent iteration of the autocorrelation function calculation is associated with an increase in the required computational resource. The latter is conditioned by the doubling of the amount of processed data at each iteration.

Results. The developed procedures for generating formant information were investigated both in the processing of model and experimental voice signals. The model signals had a low signal-to-noise ratio. The proposed procedures allow to determine more precisely the width of the spectrum of extracted formant frequencies, significantly increase the number of extracted formants, including cases at low signal-to-noise ratio.

Conclusions. The conducted model experiments have confirmed the performance and reliability of the proposed procedures for extracting formant information both in the processing of model and experimental voice signals. The results of the research allow to recommend their use in practice for solving problems of voice authentication, speaker differentiation, speech and gender recognition, intelligence, counterintelligence, forensics and forensic examination, medicine (diseases of the speech tract and hearing). Prospects for further research may include the creation of procedures for evaluating formant information based on phase data of the processed voice signal.

KEYWORDS: autocorrelation function, authentication, voice signal, speech recognition, formant information, spectrum width.

NOMENCLATURE

$\varepsilon(\tau)$ – error that occurs when calculating the autocorrelation function;

τ – delay time;

$\overline{C}_{nn}(\tau)$ – component of the autocorrelation function conditioned by noise correlation;

$\overline{C}_{ns}(\tau)$ – component of the autocorrelation function conditioned by the correlation between the noise and the useful signal;

$\overline{C}_{sn}(\tau)$ – component of the autocorrelation function conditioned by the correlation of the useful signal and noise;

$\overline{C}_{ss}(\tau)$ – component of the autocorrelation function conditioned by the correlation of the useful signal;

$C_{XX}(\tau)$ – autocorrelation function;

k – number of elements in the processed sample;

$n(t)$ – noise component, which is a stationary process;

$s(t)$ – polyharmonic voice signal;

T – signal registration period;

t – signal registration time;

$X(t)$ – additive mixture of useful and interfering signals;

x_1 – first element of the processed sample.

INTRODUCTION

In today’s digital world, where information protection is one of the most important tasks, authentication methods in information systems are becoming key components of security. When using computer systems, mobile devices, online services and electronic document management, authentication plays a crucial role in confirming users’ access rights to systems and their resources.

However, the existing types of authentication have their advantages and disadvantages, and the practice of their usage in network technologies shows their low reliability. Therefore, in recent years, intensive research has been carried out on the application of biometric user at-

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tributes in authentication systems. Among biometric authentication systems a special place belongs to voice systems, which are preferable by the criterion of cost/efficiency. Obviously, that is why the Ukrainian state-owned bank Privat is implementing voice authentication systems.

The procedures of voice authentication were based on the works on speech recognition, which dates back to the middle of the last century. The whole process of voice authentication can be divided into three stages: signal preprocessing; formation of user features; decision making about the belonging of features to a given user.

Among the features of the user voice signal at authentication the following are used: pitch frequency, formant information, cepstral and mel-frequency coefficients and others. A special place belongs to formant information, which is used not only in authentication, but also in solving a number of other tasks.

Formant refers to the resonant frequency in the human speech tract that contributes to the unique timbre and quality of a speech sound. These frequencies are created by the shape and position of the tongue, lips, and other structures of the speech tract during speech production. Formants are essential in phonetics and speech processing because they play a crucial role in distinguishing between different vowels and consonants. It is known that the computation of formant frequencies is used to recognize letters or syllables (strictly speaking – phonemes) pronounced by humans. Formant information is widely used in intelligence, counterintelligence, forensic examination, medicine (diseases of the speech tract and hearing), gender recognition. In music, formants also play an important role as they contribute to the characteristic tonal qualities of various musical instruments and vocal performance.

Formant analysis has practical applications in a variety of fields, including voice identification and authentication systems, speaker recognition, speech synthesis, virtual instrument design, and audio effects processing.

Formants play a crucial role in voice synthesis by shaping the timbre and articulation of synthesized voices, contributing to the naturalness and intelligibility of the generated speech. In voice recognition systems, formant analysis helps to identify and distinguish spoken sounds, facilitating accurate speech-to-text conversion and voice authentication.

Formants play a significant role in the formation of acoustic characteristics of speech, including regional accents. Variations in formant frequencies and resonance patterns in different languages and dialects help to distinguish regional accents, affecting the perceived pronunciation and intonation of spoken speech. Formants are also used in identifying the gender characteristics of the user.

To determine formants, frequency filters, spectral analysis, wavelet transform, neural networks, etc. are used. At the same time, spectral methods are the most widely used, but they do not always meet the requirements.

The object of study is the process of digital processing of a voice signal when generating formant information.

The subject of study is the sampling methods methods for estimation of formant information from the user's voice signal using correlation and spectral analysis.

Known estimation methods are not always effective when there is a noise component.

The purpose of the work is development and study of procedures that allow to improve the quality of formant information extraction from the voice signal of the authentication system user, especially in the presence of interference.

1 PROBLEM STATEMENT

To estimate the formant information of a voice signal in the presence of a noise component, we use the properties of the correlation function [1]. To reduce the stochastic noise component of the original signal, its autocorrelation function is used in [2, 3]. Let us consider the application of the above method to extract formant data from the voice signal information. Let the original recorded speech signal $X(t)$ be an additive mixture of a polyharmonic voice signal $s(t)$ and noise $n(t)$, which is a stationary process

$$X(t) = s(t) + n(t)\,, \tag{1}$$

where t is the time of signal registration. We assume that at the stage of preprocessing the analyzed signals are centered.

By definition, the autocorrelation function of the analyzed signal is calculated as follows [1]

$$C_{XX}(\tau) = \lim_{T\to\infty} \int_0^T X(t)\cdot X(t-\tau)dt, \tag{2}$$

where T is signal recording period; τ – delay time.

Due to the distributivity of the correlation operator, we can represent $C_{XX}(\tau)$ in the form of the following summands

$$\overline{C}_{XX}(\tau) = \overline{C}_{ss}(\tau) + \overline{C}_{nn}(\tau) + \overline{C}_{sn}(\tau) + \overline{C}_{ns}(\tau). \tag{3}$$

Let us analyze the components of the autocorrelation function. We start the analysis with the second summand $\overline{C}_{nn}(\tau)$, which, taking into account the stochasticity of noise, tends to zero, and at the point $\tau = 0$ tends to the noise variance. The third and fourth summands ($\overline{C}_{sn}(\tau)$, $\overline{C}_{ns}(\tau)$) tend to zero as the processed signals are centered. The component $\overline{C}_{ss}(\tau)$ will have a higher signal-to-noise ratio [2]. As a result, we obtain

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$$X^{'}(\tau) = \overline{C}_{ss}(\tau) + \varepsilon(\tau), \tag{4}$$

where $\varepsilon(\tau)$ is some error, which decreases with increasing integration time T.

Here we note that the autocorrelation function of the sum of periodic signals is a periodic function with the same frequency [1, 2], i.e., it contains all frequency components of the formant signals.

2 REVIEW OF THE LITERATURE

The fundamental provisions of the acoustic spectral theory of speech were formulated in the XIX century by the outstanding German scientist G. Helmholtz, which are widely used today. Let us pay attention to the works of the famous Swedish acoustician G. Fant, who also proposed a theory of distinguishing features – a universal acoustic classification of sounds. Formant information plays a significant role in this classification.

Various methods are used to obtain individual parameters of the speaker's voice, but formant analysis provides the most robust identification characteristics. It is empirically proved that four formants are sufficient to characterize speech sounds. In most cases, the first two formants are sufficient to distinguish vowel sounds, but almost always the number of formants in the sound spectrum is greater than two, indicating more complex relationships between articulation and acoustic characteristics of the sound than if only the first two formants are considered. It is the third and fourth formants that give an idea of the individual features of the speaker's pronunciation, as they capture side resonant frequencies. Formants together with other characteristics of the speech signal represent a qualitative dynamic evaluation of the speaker [4].

Determination of formant frequencies as local peaks in the amplitude spectrum of a speech signal still has significant difficulties. These difficulties are related both to the peculiarities of sound generation in the speech path and to external conditions [5].

All modern works in the field of formant analysis can be divided into several classes. The first class includes works that consider methods of formant analysis based on a generalized mathematical apparatus. In this case, the works lack a phonetic approach and do not take into account the physiological features of the human speech tract. The main attention is paid to the procedures of digital processing of nonstationary polyharmonic (polyfrequency) signal. The procedures are mostly based on the Fourier transform. Recently, cepstral analysis, wavelet transforms [6], etc. have been used for this purpose.

Another class of methods for estimating formant information is based on taking into account the peculiarities of the human speech path. For example, [7] proposes to construct the state vector of an a priori specified dynamic system (in this case, the speech path) based on the application of a recursive filter (Kalman filter). For the LPC-transformation method, [8] additionally introduces a procedure for "smoothing" formant spikes using the Newton-Raphson fast convergence algorithm.

Recently, many works have been published, in which the issues of diagnostics of diseases of the speech tract and hearing are considered [9].

The works in which neural networks are used, are considered separately [10, 11].

3 MATERIALS AND METHODS

To explain the processing procedures, let us further proceed to digital (discrete) signals. For simplicity of explanation, we will assume that a fragment of the speech signal (line vector) X containing five samples is processed. Obtaining the first half of the elements of the autocorrelation function is connected with multiplication of this vector by a matrix, namely

$$(x_1, x_2, x_3, x_4, x_5) \cdot \begin{pmatrix} x_5 x_4 x_3 x_2 x_1 \\ 0\ \ x_5 x_4 x_3 x_2 \\ 0\ 0\ \ x_5 x_4 x_3 \\ 0\ 0\ 0\ \ x_5 x_4 \\ 0\ 0\ 0\ 0\ \ x_5 \end{pmatrix}. \tag{5}$$

The second half of the autocorrelation function is obtained using the following matrix operations

$$(x_1, x_2, x_3, x_4, x_5) \cdot \begin{pmatrix} x_2 x_3 x_4 x_5 0 \\ x_3 x_4 x_5 0\ 0 \\ x_4 x_5 0\ 0\ 0 \\ x_5 0\ 0\ 0\ 0 \\ 0\ 0\ 0\ 0\ 0 \end{pmatrix}. \tag{6}$$

In (6), to obtain a square matrix, the latter is supplemented with five columns consisting of zeros. As a result, we obtain an autocorrelation function containing nine elements, which is normalized accordingly. If necessary, we can calculate the autocorrelation function from the obtained samples. Naturally, the initial vector and the structure of the used matrices are changed. The number of processed elements at each processing cycle is doubled $(2 \cdot k)$, and the number of computational operations is proportional to the value of k^2.

After calculating the autocorrelation function, a fast Fourier transform is applied to the results. As a result, we obtain the amplitude-frequency spectrum from the autocorrelation function of the voice signal. In the simplest case we can perform threshold processing of the obtained spectrum and select formant frequencies. If necessary (low signal-to-noise ratio) processing procedures are repeated.

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4 EXPERIMENTS

To verify the performance and efficiency of the considered methodology, we perform processing of a model signal. The model signal included two harmonics: the first component had a frequency value of 250 Hz and a unit amplitude, and the second component had a frequency value of 1000 Hz and a halved amplitude. The generated signal is shown in Fig. 1.

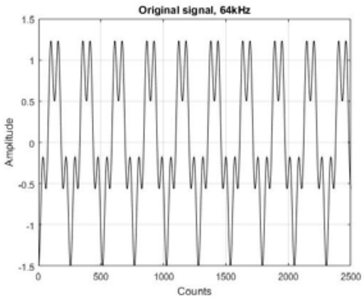

Figure 1 – Processed model signal

The sampling frequency of the considered signal is 64 kHz, the number of processed signal samples is 2500.

Then the model signal was additively supplemented with Gaussian noise. As a result, the signal-to-noise ratio by power of the processed mixture was approximately 0.7 dB. The signal received for processing is shown in Fig. 2.

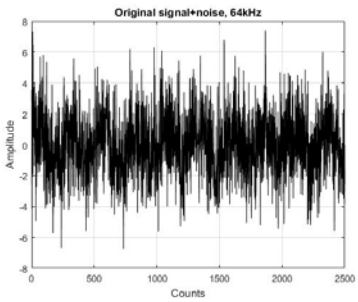

Figure 2 – Mixture of model signal and noise

Traditionally, filter-based methods have been used to determine formant information, but recently spectral procedures have been favored.

Fig. 3 shows the amplitude-frequency spectrum of the processed mixture.

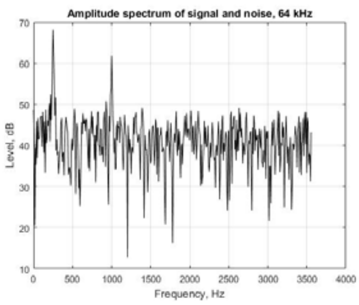

Figure 3 – Amplitude-frequency spectrum of the processed mixture

The analysis of the presented spectrum allows us to determine the frequencies of the model signal. The maxima of the spectrum correspond to the frequencies of the model signal, namely 250 and 1000 Hz. However, the width of formant frequencies is rather difficult to determine.

Further, the same mixture was processed according to the proposed methodology. The processing results after five cycles of calculating the autocorrelation function and calculating its spectrum are presented in Fig. 4. The maxima of the spectrum also correspond to the frequencies 250 and 1000 Hz. The width of the formant frequency spectrum is determined quite accurately. Thus, the proposed technique allows us to determine the frequencies of the components of the polyharmonic signal.

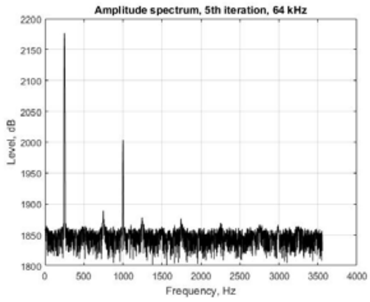

Figure 4 – Amplitude-frequency spectrum from the autocorrelation function

Analysis of the obtained spectrum makes it possible to draw a conclusion about the increase in the signal-to-noise ratio of the selected harmonics and their narrower spectrum width. The latter is essential for accurate determination of the values of format frequencies. Further we proceed to the similar processing of the experimental voice signal of the authentication system user.

5 RESULTS

Let us illustrate the results on the example of voice signal processing. The user pronounced “one” as an experimental signal. Fig. 5 shows the experimental voice signal containing 37000 samples recorded from a microphone with a sampling frequency of 64 kHz.

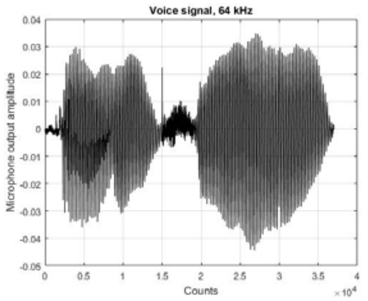

Figure 5 – Experimental voice signal

The amplitude-frequency spectrum of the analyzed signal is shown in Fig. 6.

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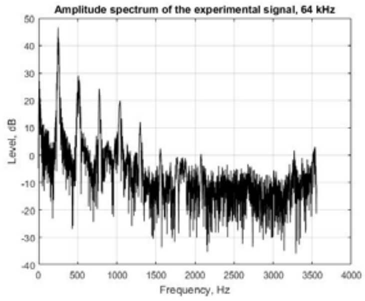

Figure 6 – Amplitude-frequency spectrum of the analyzed signal

Analysis of the spectrum shows that six maxima of formant frequencies can be identified. However, there are difficulties in determining the width of the formant spectrum and determining the frequencies of the maxima. Naturally, there will be problems with the construction of the envelope of the analyzed signal spectrum.

The results of threshold processing of this spectrum are presented in Table 1.

Table 1.

Formant number	F1	F2	F3	F4	F5
Spectrum level, dB	65	53	51	48	40
Frequency, Hz	258	524	782	1040	1297

The results of processing according to the proposed method will be illustrated during the processing of a fragment of the considered signal. Fig. 7 shows a fragment of the investigated voice signal including a part of the phoneme “o”, and its spectrum is shown in Fig. 8.

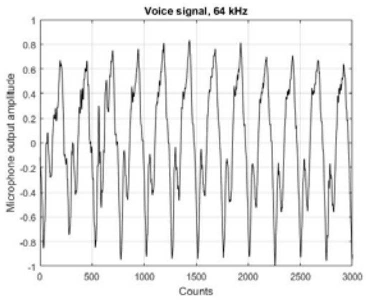

Figure 7 – Fragment of the experimental voice signal

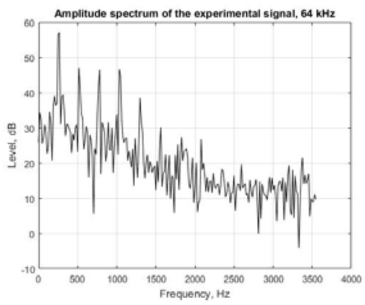

Figure 8 – Amplitude spectrum of the experimental voice signal fragment

Threshold processing (threshold value 35 dB) of the obtained spectrum allows to identify five formant frequencies. The results are presented in Table 2.

Table 2 – Spectrum thresholding results, threshold is 35 dB

Formant number	F1	F2	F3	F4	F5
Spectrum level, dB	57.1	47.1	46.5	46.7	38.57
Frequency, Hz	266	516	782	1032	1297

The results of processing a fragment of the experimental signal using the method proposed above are presented in Figs. 9–11.

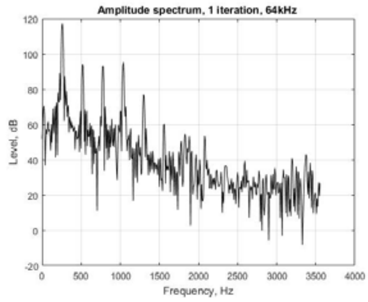

Figure 9 – Amplitude spectrum after first iteration

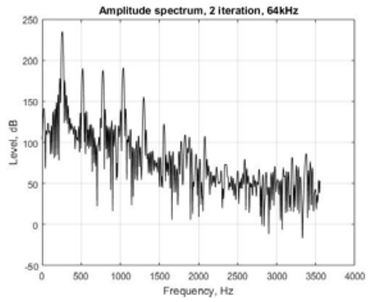

Figure 10 – Amplitude spectrum after the second iteration

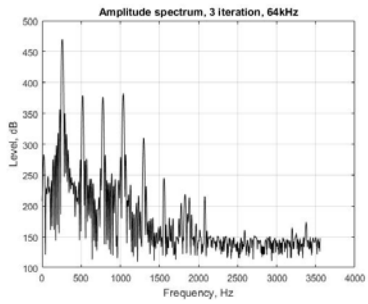

Figure 11 – Amplitude spectrum after the third iteration

The analysis of the presented spectra gives grounds to conclude that the proposed processing technique allows to increase the signal-to-noise ratio.

The results of the autocorrelation function spectrum processing after the first iteration with a threshold of 75 dB are presented in Table 3.

Table 3 – Results of spectrum thresholding, threshold 75 dB

Formant number	F1	F2	F3	F4	F5
Spectrum level, dB	117	94.2	93.1	93.3	77
Frequency, Hz	258	516	774	1032	1297

Table 4 shows the results of the autocorrelation function spectrum processing after the first iteration with a threshold of 50 dB.

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Table 4 – Results of spectrum thresholding, threshold 50 dB

Formant number	F1	F2	F3	F4	F5	F6	F7	F8
Spectrum level, dB	117	94	93	93	77	60	55	54
Frequency, Hz	258	516	774	1032	1297	1563	1829	2079

As evidenced by the results, the proposed methodology allows to determine up to eight formant frequencies, which can positively affect the quality of voice authentication systems.

6 DISCUSSION

The use of the spectrum after the second and subsequent iterations does not give better results, however, it requires a significant computational resource. Therefore, when estimating formant frequencies, it is reasonable to limit ourselves to one iteration of the autocorrelation function calculation.

Let us briefly analyze the results of the model experiment. We begin the analysis by considering Tables 1 and 2. The first two formant frequencies are different. It is known that they are determined by the content of the voice signal. Therefore, this distinction of frequencies is justified. The third formant frequency depends on the speech apparatus of the user of the authentication system. This explains that these frequencies of the third formant are equal. The fifth formant frequency is also equal.

Now let us analyze the contents of Tables 2 and 3, namely, the results of traditional spectral methods for determining formant frequencies and the proposed methodology. The normalized correlation coefficient of both spectral density and formant frequencies is more than 0.99. However, the first three formant frequencies have a small difference. The fourth and fifth formant frequencies are the same. The second, third and fourth formant frequencies calculated by the proposed method are multiples of the first formant frequency. This fact deserves attention and requires further investigation.

CONCLUSIONS

The relevant scientific problem of development and research of procedures that allow to significantly improve the quality of formant information extraction from the voice signal of the authentication system user at low signal-to-noise ratio was solved. The object of the research is the process of generating formant information in various applications.

The scientific novelty of the obtained results lies in the fact that for the first time a method of formant information refinement is proposed on the basis of procedures for calculating the autocorrelation function of the analyzed fragment of the voice signal (mismatch function), to which traditional spectral methods of formant frequencies determination are subsequently applied. The use of the autocorrelation function as initial information, first of all, allows to increase the signal-to-noise ratio and more accurately determine the width of the formant frequency spectrum.

For the investigated calculation methods, the normalized correlation coefficient of both spectral density and formant frequencies is more than 0.99.

The results of the model experiment indicate the following.

In the process of formant frequencies estimation, calculation of one iteration of the autocorrelation function can be enough. Traditional spectral methods for determining formant frequencies do not have high accuracy, first of all, in determining the width of the formant frequency spectrum.

The proposed technique allows to determine more formant frequencies more accurately, which can significantly affect the determination of the envelope spectrum of the investigated voice signal.

The obtained results can be used in speech recognition, forensics, forensic examination, voice authentication.

Prospects for further research include the study of the proposed method for extracting formant information from the phase data of the voice signal of the authentication system.

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ОЦІНКА ФОРМАНТНОЇ ІНФОРМАЦІЇ З ВИКОРИСТАННЯМ АВТОКОРРЕЛЯЦІЙНОЇ ФУНКЦІЇ ГОЛОСОВОГО СИГНАЛУ

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АНОТАЦІЯ

Актуальність. Розглядається актуальне наукове завдання отримання біометричних ознак користувача системи голосової автентифікації, які дозволяють істотно підвищити її надійність. Виконано оцінка формантної інформації з голосового сигналу, яка входить в шаблон користувача системи голосової автентифікації і широко використовується при обробці мовних сигналів в інших додатках, у тому числі і за наявності шумових складових, що заважають. Особливістю роботи є те, що дослідженню піддається полігармонійний сигнал.

Мета роботи – розробка процедур формування формантної інформації на основі результатів розрахунку автокореляційної функції аналізованого фрагмента голосового сигналу та подальшого їх спектрального аналізу.

Метод. Пропонуються процедури формування формантної інформації у процесі цифрової обробки голосового сигналу. Спочатку розраховується автокореляційна функція аналізованого фрагмента голосового сигналу. На основі результатів оцінки автокореляційної функції розраховується амплітудно-частотний спектр, з якого вилучається формантна інформація, наприклад, за допомогою порогової обробки. При низькому відношенні сигнал/шум аналізованого фрагмента голосового сигналу розрахунок автокореляційної функції доцільно виконувати ітераційно. Останнє дозволяє підвищити співвідношення сигнал/шум та ефективність виділення формантної інформації. Однак кожна наступна ітерація розрахунку автокореляційної функції пов'язана зі збільшенням необхідного обчислювального ресурсу. Останнє зумовлено подвоєнням кількості даних, що обробляються при кожній ітерації.

Результати. Розроблені процедури формування формантної інформації досліджено як при обробці модельних, так і експериментальних голосових сигналів. При цьому модельні сигнали мали низьке відношення сигнал/шум. Запропоновані процедури дозволяють більш точно визначити ширину спектра вилучаємих формантних частот, значно збільшити кількість формант, що виділяються, в тому числі і при низькому відношенні сигнал/шум.

Висновки. Проведені модельні експерименти підтвердили працездатність і достовірність запропонованих процедур отримання формантної інформації як при обробці модельних, так і експериментальних голосових сигналів. Результати досліджень дозволяють рекомендувати їх до використання на практиці для вирішення завдань голосової автентифікації, розрізнення дикторів, розпізнавання мови та статі, розвідки, контррозвідки, криміналістики та судової експертизи, медицини (хвороби мовного тракту та слуху). Перспективи подальших досліджень можуть включати створення процедур оцінки формантної інформації на основі фазових даних, оброблюваного голосового сигналу.

КЛЮЧОВІ СЛОВА: автокореляційна функція, автентифікація, голосовий сигнал, розпізнавання мови, формантна інформація, ширина спектру.

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METHOD OF DETERMINING THE PARAMETER OF QUALITATIVE EVALUATION OF A WEB FORUM

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ABSTRACT

Context. The development of new types of virtual environments is an urgent task of informatisation of modern education, since such services allow enhancing the quality of educational services and contribute to a deeper assimilation of new knowledge by students. A web application proposed in this paper has been built using modern approaches to creating web pages using the .NET programming language, Bootstrap and ASP.NET MVC frameworks, Azure cloud solutions and Azure SQL databases, which has enabled the simplification of software development by distributing functions between the application modules and provided the flexibility, performance, and security necessary to work with relational data. The effectiveness of the application in the educational process has been experimentally tested using the method of determining the qualitative evaluation of the web forum usefulness parameter, which was developed by introducing an informative parameter of the discussion quality based on the *h*-index (sometimes called the Hirsch index or Hirsch number).

Objective. To build a mathematical model of a web forum and develop a method of determining the qualitative evaluation of the parameter of usefulness of discussions in the created web application, which would allow improving the quality of educational and scientific activities in a higher education institution.

Method. A method of determining the parameter of qualitative evaluation of a web forum using the *h*-index has been developed, which enabled analysing the interest in covering the trends of discussion on the forum pages and planning on its basis further work of the forum as a tool of a virtual learning environment.

Results. Based on the analysis of the results of the implementation of the web application in the educational process of the Department of Information Technologies Vasyl Stefanyk Precarpathian National University, the user activity of posts has been analysed and the effectiveness of discussions of the proposed topics on the forum pages has been determined using the introduced activity parameter.

Conclusions. A mathematical model of a web forum has been built, and the application has been implemented using modern approaches to software development using an optimised MVC architecture, which enabled simplification of creating a service by distributing responsibilities between the application modules and facilitating testing and technical support of the service.

The scientific novelty of the study is the development of a method of evaluating the usefulness of discussions in a web forum by introducing a new informative quality parameter, the use of which allowed broadening the scope of existing limitations in quantitative analytics of discussions and feedbacks in popular services. Experimental studies carried out on the basis of a higher education institution have confirmed the effectiveness of the method application to improve the quality of educational services. The practical significance of the obtained results is the development of a software product as a tool of the virtual learning environment of a higher education institution.

KEYWORDS: virtual environment, web forum, mathematical model, cloud technologies, activity parameter, method of qualitative evaluation of a web forum.

ABBREVIATIONS

HEI is a Higher Education Institution;
WBL is a Web-Based Learning;
LMS is a Learning Management System;
CC is a Cloud Computing;
SQL is a Structured Query Language;
MVC is a Model-View-Controller;
B is a Byte;
ZB is a Zettabyte.

NOMENCLATURE

Forum_i is a mathematical model of the forum;

ForumName_i is a name of a specific forum for discussion;

CreatedBy_i is a forum member who created the discussion;

$\text{Content}(\text{Forum}_i)$ is a content of the discussion;

User_i is a user model;

$N^{(\text{User})}$ is a number of forum users;

Email_i is a user's email address;

PaswordHash_i is a user's password in the form of a hash;

UserName_i is a username;

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$IsActive_i$ is a Boolean variable of the user activity;

$MemberSince_i$ is a date of registration on the forum;

$ProfileImageUrl_i$ is a path to the profile photo;

$Rating_i$ is a user rating;

$Topic(Forum_i)$ is a set of discussions that belong to the forum $Forum_i$;

$TopicName_i$ is a discussion title;

$TopicAuthor_i$ is a discussion author;

$TopicDate_i$ is a date of creation of the discussion;

$Post(Topic_i) = \{Post_i\}$ is a set of publications in the i^{th} discussion;

$Post_i$ is a model of publications;

$PostAutors_j$ is a set of users participating in the discussion;

$N_i^{(PostAutors_j)}$ is a number of publications of the j^{th} author in the i^{th} discussion;

$\{m\} = \{N_i^{(PostAutors_j)}\}$ is a set, each element of which indicates the number of publications of the j^{th} author in the i^{th} discussion;

H_i is a *h*-index of the discussion $Topic(Forum_i)$;

K_i is a parameter of the discussion activity $Topic(Forum_i)$.

INTRODUCTION

The past few decades, with the intensive development of modern information technologies and the availability of the Internet, have been characterised by unique opportunities for self-education that are constantly evolving and improving. The World Wide Web has become a source of intellectual activity for modern students and teachers, who have unlimited opportunities to gain knowledge, improve their skills and develop professional skills [1].

The educational process and the university management system are constantly being digitised, which are the main factors that allow not only enhancing the management effectiveness by automating various activity areas of a higher education institution (HEI), but also raising its social significance as a centre for generating and disseminating new knowledge and information, ensuring its competitiveness and the quality of professional development training [2].

One of the popular areas and trends in modern education is the introduction of web-based learning (WBL) and the use of various web-based learning environments, such as automated learning systems, web portals, and cloud-based LMS. Web forums are also a leading modern and relevant tool of informatisation, which are the resources that provide an opportunity to exchange ideas and opinions between users from different countries and regions on various topics such as education, science, technology, politics, sports, medicine, art, and others.

Such web applications appeared almost as soon as the Internet era began. The conventional approach to organising a discussion or forum began with standard online bulletin boards and has evolved smoothly in response to new user needs, having become an integral part of the World Wide Web. Today, forums serve as the main mechanism for ordinary users to express their opinions on any topic, as well as for teachers, students and researchers to find answers to relevant self-education questions.

Comments made in discussions are usually managed by those who are responsible for this and checked for compliance with the terms and requirements of the site. When a post on a forum receives a certain amount of attention and comments, you can see how its display resembles a tree structure. That is, a single post can be seen as the root, and each reply is like the beginning of a corresponding branch. Some trees are wide and shallow: everyone responds to the author's thesis; other trees are narrow and deep: when two people argue "back and forth" and only a few users participate in the discussion of a common topic.

Notwithstanding that such forums were created at the beginning of the Internet development, they are still popular among users and occupy one of the highest ranking positions among the most visited websites in the world.

Therefore, the development of new types of virtual environments as tools of informatisation of education, in particular, web forums that would account for the advantages of known solutions and eliminate their disadvantages to functionally improve the interaction of the web service with the user is an urgent scientific and applied task that requires in-depth theoretical and software research.

The object of the study is the process of developing a web forum as a model of a web-based learning environment.

The subject of the study is a method for determining the qualitative evaluation of the usefulness parameter of discussions on a web forum.

The aim of the work is to build a mathematical model, develop a web application on its basis to create a modern software product and study the effectiveness of discussions on topics using the method of determining the qualitative evaluation of the usefulness of discussions, which will improve the quality of educational and scientific activities at higher education institutions.

To achieve these goals, the paper solves the following problems:

– to analyse known software solutions for creating web forums, to identify their advantages and disadvantages and to account for them in own development;

– to build a mathematical model of a web forum for the implementation of the application software logic;

– to develop a method of qualitative evaluation of the usefulness of discussions;

– to programmatically develop the service using modern technologies for building web pages;

– to carry out an experimental test of the application of the proposed development during the organisation of

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the educational process in a higher education institution, and to substantiate the effectiveness of the research results and their feasibility in the educational sector.

1 PROBLEM STATEMENT

When creating modern web-based learning environments, developers face a large number of challenges related to the problems of how to account for the features of organising virtual communication between participants in the educational process, issues of software implementation based on the use of development tools and the choice of services for further deployment. In addition, a key stage for possible introduction of such services into the educational process is to substantiate the effectiveness of their use using both known and own developed research methods. Therefore, there is a need to both create new types of learning environments and to develop effective and reasoned methods for studying the feasibility of their use.

Assume that the model of discussion $Topic(Forum_i)$ started on a forum $Forum_i$ by a user $TopicAuthor_i$ is represented by the following characteristics:

$$Topic(Forum_i) = < TopicName_i, TopicAuthor_i, TopicDate_i, Post(Topic_i), K_i > . \quad (1)$$

To qualitatively evaluate the activity of the discussion $Topic(Forum_i)$, a parameter $K_i = \frac{H_i}{t}$ was introduced (2), which is defined as the ratio of the *h*-index H_i of the discussion $Topic(Forum_i)$ to the time t, during which the activity parameter is evaluated [3].

For further implementation of the software, a mathematical model of a web forum $Forum_i$ is needed based on modern approaches to building web pages using the .NET programming language, Bootstrap, ASP.NET MVC frameworks and data storage in Microsoft Azure cloud services (Azure SQL, Azure Blob), and the effectiveness of the proposed service in the educational process should be studied based on the method of evaluating the proposed discussion usefulness indicator K_i.

2 REVIEW OF THE LITERATURE

The studies of both domestic and foreign scientists and developers show a growing interest in the creation of various web applications, which, owing to the use of an accessible and user-friendly interface, have become an indispensable source of information for modern people. Virtual subject communities have gained particular popularity, the number of which is constantly growing and reaching a wider audience [4].

The most quoted definition of ‘virtual communities’ among foreign and Ukrainian researchers is that of H. Rheingold: “Virtual communities are social associations of people that grow out of a network when a group of people hold an open discussion of a problem for a long enough time and do so in a humane enough way to form a network of their personal relationships in cyberspace” [5].

Scientific research aimed at studying virtual communities is reflected in the paper [6], the development of a classification of virtual environments is carried out in the paper [7], paper [8] analyzes the research of foreign scientists on this issue.

To create and maintain virtual environments, appropriate cloud technologies are required, the most common of which is cloud computing (CC). The concept of CC is to provide end users with remote access to dynamically scalable computing resources, services, and applications (including operating systems and infrastructure), which are maintained and updated by a service provider [9].

In 2023, about 50 ZB of information was stored in the cloud (1 ZB = 270 B). This figure is expected to reach 100 ZB by 2025.

According to the analytical resource *datereportal.com*, forums as tools of virtual communities are still at the top of the most visited websites in the world. In particular, the following forums are currently considered to be the most popular:

– *Reddit* [10] is one of the best known forums in the world today, founded in 2005, reaching around 330 million visitors monthly and up to 57 million unique active visitors daily;

– *Quora* [11] is an online forum designed to increase the knowledge level of programmers and other computer science professionals with an estimated 300 million users;

– *Stack Overflow* [12] is an online forum where discussions on various trends in programming are ongoing with the involvement of highly qualified experts.

As for forums in the education sector, the most popular forum in Ukraine is *Osvita.ua*.

The advantages and disadvantages of the most popular forums are summarised in Table 1.

Based on the analysis of popular forums, it was determined that despite so many positive aspects of each of them (for example, the creation of thematic forums, the possibility to filter posts, multilingual extensions, the availability of numerical analytics of views and posts), the main disadvantage is the lack of a qualitative parameter for evaluating each discussion, which can be used to determine the qualitative characteristics of the interest of users in the relevant topic.

Therefore, the result of this work is the development of a web platform where users can create their own forums, participate in discussions, share information with other users and study the effectiveness of its quality use using the method of evaluating the usefulness of web forum discussions.

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Table 1 – Advantages and disadvantages of popular forums

Forum name	Advantages	Disadvantages
Reddit	– the possibility to create your own thematic forums (*subreddits*); – the availability of a voting system; – the use of various moderation algorithms to ensure the comfort and safety of users; – the availability of statistics on the number of posts and participants at the current time.	– restriction of freedom of speech by the moderator; – difficulty in finding useful information (due to the large number of messages); – most information is available only in English.
Quora	– simple and user-friendly interface; – the possibility to use the division of questions into categories; – an edit function that allows users to edit and improve questions and answers in a foreign language; – multilingual extension; – availability of statistics on the number of positive and negative votes.	– the need for a continuous expert feedback channel to comment on current issues; – intrusive advertising and sending unnecessary emails that may annoy users.
Stack Overflow	– standard format and arrangement of questions and answers; – the possibility of publishing codes and program examples; – ensuring a plurality of options for answers to the questions posed; – possibility to filter publications (latest, active, unanswered).	– the quality of answers is not always high enough; – oversaturation of the site with questions from various areas; – high dependence on the number and qualifications of involved experts.
Освіта.ua	– access to the publication of posts and blogs for registered users; – the possibility of receiving answers to any questions related to education and training both in Ukraine and abroad; – the possibility of obtaining analytics on the activity of visitors (answers, views).	– oversaturation of the site with questions from parents and teachers, which do not always relate to the educational process; – the absence of a qualitative parameter for evaluating the activity of discussions.

3 MATERIALS AND METHODS

A web forum is a type of virtual learning environment in which the information content consists of a set of forums, a set of discussions, and a set of messages. A mathematical model of a web forum is organised as a hierarchy, with the forum itself at the top level.

The structure of the web forum platform is as follows:

$$\text{Forums} = \langle \text{Forum}_i, \text{User}_i \rangle. \tag{3}$$

Consider the model of a web forum (3). A forum, as an integral part of a service, has its own topic and target audience. It is characterised by the following parameters:

$$\text{Forum}_i = \langle \text{ForumName}_i, \text{CreatedBy}_i, \text{Content}(\text{Forum}_i) \rangle.$$

A user of a web forum can be considered any person who visits the site, reads or interacts with its information content in the form of discussions and answers to questions. The model of a web forum user User_i is given in the form:

$$\text{User}_i = \langle \text{Email}_i, \text{PaswordHash}_i, \text{UserName}_i, \text{IsActive}_i, \text{MemberSince}_i, \text{ProfileImageUrl}_i, \text{Rating}_i \rangle.$$

Then a set of the forum users is represented as:

$\{\text{User}\} = \{\text{User}_i\}_{i=1}^{N^{(\text{User})}}$ is a set of the forum users.

The information content of the forum discussion (topic) $\text{Content}(\text{Forum}_i)$ is as follows:

$$\text{Content}(\text{Forum}_i) = \langle \text{Topic}(\text{Forum}_i), \text{PostAutors}_j \rangle.$$

Each discussion $\text{Topic}(\text{Forum}_i)$ is described by the following parameters:

$$\text{Topic}(\text{Forum}_i) = \langle \text{Post}(\text{Topic}_i), N_i^{(\text{PostAutors}_j)}, m \rangle.$$

A discussion is actually a key part of a forum, which can be created by the administrator or another registered user. It is a collection of messages related to a single topic and arranged in a chronological order, as shown in (1).

In each discussion, users expect that there will be some kind of post from other forum participants. Forum posts can be considered as the smallest piece of information content that has an atomic structure.

The *h*-index H_i for the i^{th} discussion will be calculated similarly to its calculation for scientific papers, i.e. as a function of the number of publications and their authors. Assume that 10 forum users took part in the discussion of the i^{th} discussion, each of them published a certain number of posts. For example, user 1 posted 1 post, user 2 posted 2 posts, user 3 posted 4 posts, ..., user 10 posted 7 posts. Then the set $\{m\}$ for this example will include the following elements:

$$\{m\} = \{1, 2, 4, 5, 3, 1, 6, 6, 2, 7\}.$$

The *h*-index H for this discussion, will be equal to 4, as this is the minimum number of posts that have been made by users with at least 4 posts (in this case, the number of such users is 5). The index cannot be equal to 5 because the number of users with at least 5 posts is 4.

To determine the *h*-index according to the described method, an algorithm has been developed that calculates the value of H depending on the number of users p_k and their publications m_k in a specific discussion (Fig. 1):

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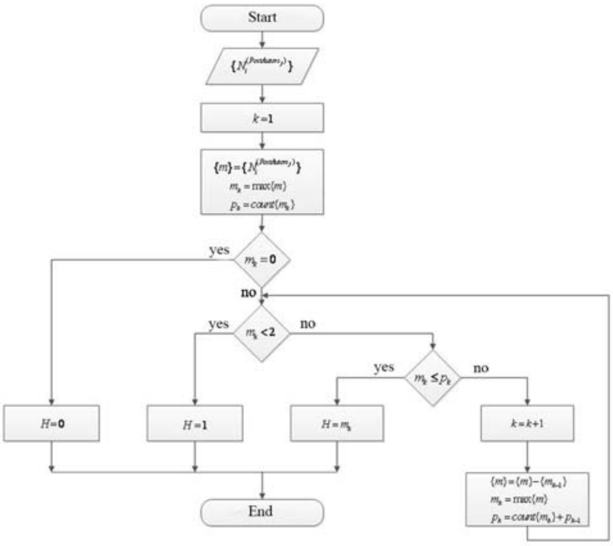

Figure 1 – Algorithm for determining the *h*-index for discussion

The activity indicator of the i^{th} discussion over time t according to formula (2) will be determined as the ratio of the calculated index H to the time during which the discussion is being analysed.

The mathematical model built in this way serves as the basis for the software implementation of the web application, which is made using a number of modern development technologies and cloud services.

In particular, the front-end part of the service was implemented using the Bootstrap framework, which is a powerful tool for creating a user interface [13].

Asp.NET MVC, a reliable and flexible framework for creating web applications running on .NET, was used on the back-end of the application [14]. MVC is a design pattern that divides the logic of the application into three main components: a model (*Model*), a presentation (*View*) and a controller (*Controller*). This architecture provides built-in support for scaling, which allows expanding the forum with the growth of users and requests, and facilitates the division of functionality into separate components, which makes it easier to develop, test, and maintain the project [15].

The use of cloud services allows developers, on the one hand, to focus directly on coding, without worrying about the support and maintenance of the infrastructure, on the other hand, the services provide high flexibility, scalability, and performance of the application [16].

Based on the proposed mathematical model of the forum (3) and in accordance with the MVC architecture, a graphic model of the logical structure of the service is presented (Fig. 2).

This model includes properties that describe various aspects of the forum, its characteristics and relationships with other models (for example, *PostModel* for describing the structure of posts, *PostReplyModel* for a described structure for replies to posts).

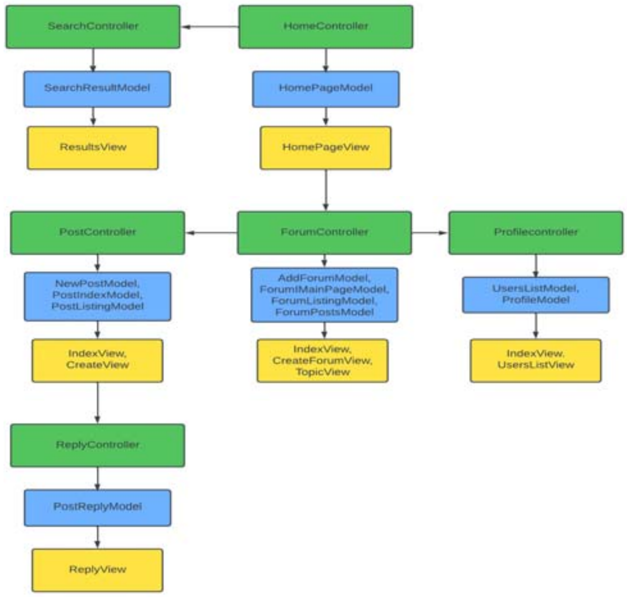

Figure 2 – Graphical model of the MVC logical structure of the *ForumModel* web forum

For each user, after visiting the platform, to be able to receive a list of forums in a proper form (Fig. 3), a controller *ForumController* was developed. It describes the logic of how forums should be displayed. First, there is a request to the database, which is structured according to an additional *ForumListModel* model.

To calculate the efficiency ratio, the *PostReplyModel* module was used, the use of which allows implementing the functionality for calculating the efficiency ratio of each discussion according to the algorithm presented in Fig. 1.

In particular, Fig. 3 shows the view of the forum for an ordinary user, which displays the list of existing discussions and the numerical values of the corresponding usefulness coefficients K_i:

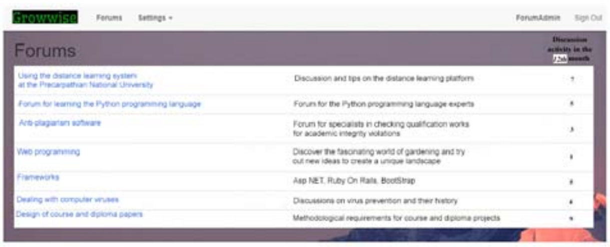

Figure 3 – Screenshot showing the list of existing discussions and indicators of their activity

Thanks to the MVC philosophy, each element harmoniously interacts with other components of the model. The example page in Fig. 3 demonstrates how, after the user opens the list of forums, a view activates the controller and interacts with the model to provide the user with the necessary information about the activity of each discussion.

Also, the developed web forum enables implementing the following functionality:

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1) search requests – implemented using a *HomePageSearchController* controller, in which a method has been added that performs the search function among existing forums and discussions;

2) the possibility to display a dynamic navigation menu for different user roles. To do this, a *ProfileController* was created, which describes a function about where the information for this page should come from;

3) the possibility of participating in discussions and publishing answers. To implement this functionality, a *ReplyController* was created, which describes a function that processes a new reply according to the *PostReplyModel* that was created earlier.

In the first release of the project, the MySQL database was used to ensure the necessary storage and organization of data, the use of which allows working efficiently with data and ensures stable and scalable development of the application (Fig. 4):

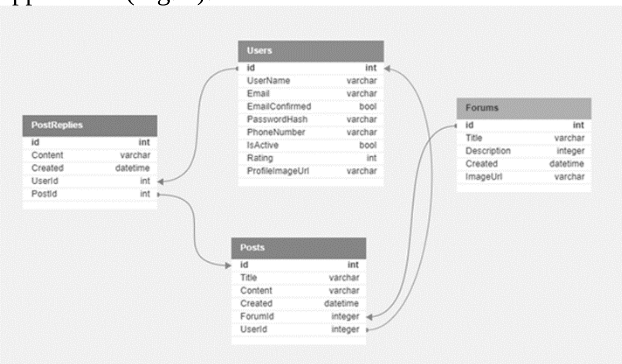

Figure 4 – Data schema diagram with corresponding relationships between the tables

In the process of testing the development, a transition to Azure SQL was made, which is a fully managed database service in the cloud and provides high data security. This transition allows using all the advantages of an Azure account and provides more flexible and scalable database management, as well as improved performance and availability of the application [17].

To successfully prepare data for migration, special tools such as Azure Database Migration Service or Azure Data Migration Assistant were used, which enabled performing both the analysis and planning of the data structure and the conversion of data types, as well as ensuring compatibility between MySQL and Azure SQL [18] (Fig. 5):

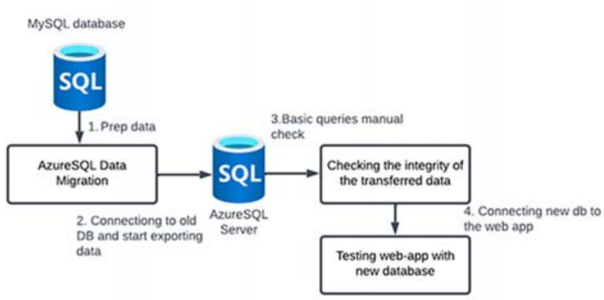

Figure 5 – Database migration scheme in Azure SQL Cloud

As soon as the migration was completed, the correct functioning of the application was tested and verified using the Azure SQL database.

4 EXPERIMENTS

The proposed service has passed the testing stage and has been successfully implemented in the organization of the educational process and scientific activity by teachers and students of the Precarpathian National University. This enabled realizing the creative ideas of contributors and to use non-standard approaches to solving problems in the process of studying at a HEI, to activate scientific and educational and cognitive activities of teachers and students.

Thanks to the involvement in the discussion of an increasingly wide range of users, both from the side of teachers and the student community, in a relatively short period of use (6 months), a number of important topics from the field of programming, problems of distance education, passing of educational and practical training by students, finding a place of employment and a number of others were covered and commented on the pages of the application (Fig. 6.):

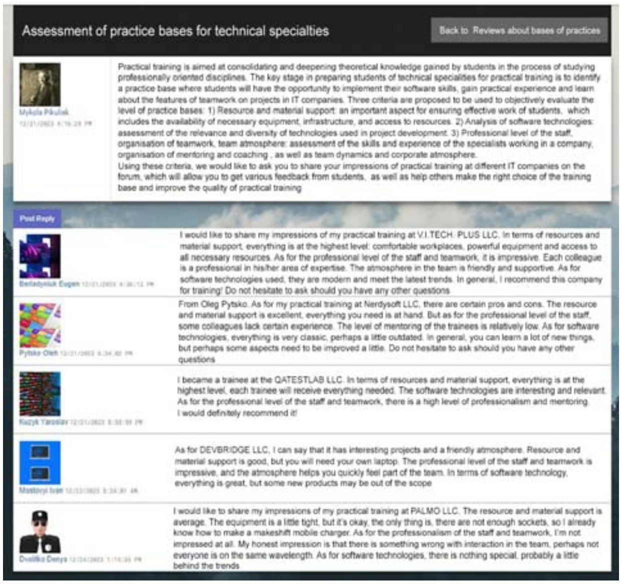

Figure 6 – View of the page with the published posts for the discussion

5 RESULTS

Based on the obtained indicators of activity, the interest in the topic of discussions at the forum was analysed over several months.

Fig. 7a and 7b present graphs of the analysis of the activity indicator for the months of December 2023 and January 2024, respectively.

The result of the implementation of the proposed service was not only an increase in the level of knowledge of students and the activation of scientific cooperation of teachers, but also concrete practical results of using the forum, which indicates an improvement in the quality of the educational process.

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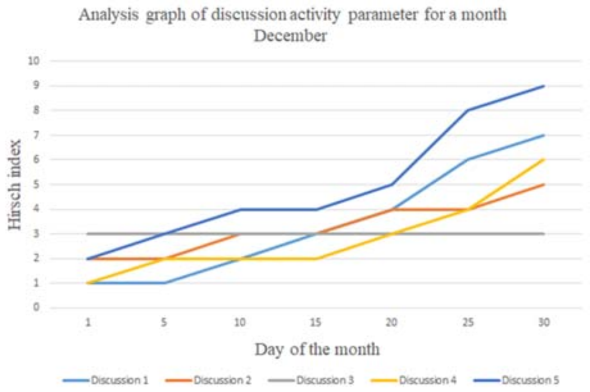
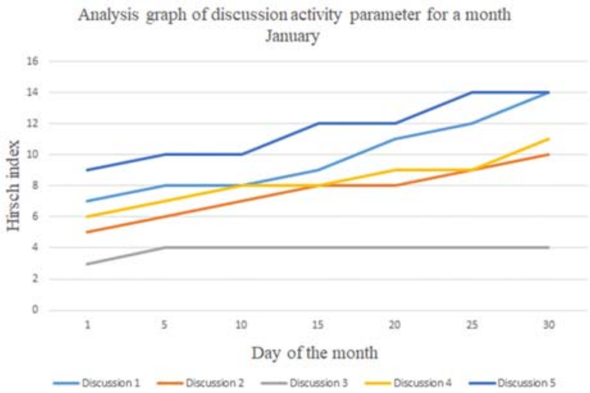


a



b

Figure 7 – Analysis graphs of activity indicators:
a – the month of December, b – the month of January

Thus, according to the results of the discussion by the students of the 4th year of the "Software Engineering" program on the topic of the quality of resource and information support of practical training bases, significant deficiencies were found in three practice bases in terms of providing the students with proper conditions for the implementation of the practical training program and the participation of the students in the development of software projects.

As a result of the analysis of the students' posts at the meeting of the Department of Information Technologies, a decision was made about the impracticality of further sending the students of the department for the training to the companies designated in this way, which will improve the quality of practical training of students.

Also, the discussion on the proposed service helped five 4th year students (which is 18% of the total number of students of the SE-41 group) to decide on the place of further employment, because as a result of the training, the students received invitations to work in corresponding IT companies.

For today, teachers and students of other programs are being involved in active discussion on the pages of the forum on various topics, which changes the role of participants in the modern educational process and promotes the search for new non-standard solutions in the field of education.

6 DISCUSSION

The development of web forums is an ongoing process, in which attempts are actively made to improve both the design and the introduction of new functionality, which contributes to the further development of this platform.

The use of the introduced qualitative parameter of the discussion activity allows constant monitoring the analytics of the user activity on the web forum and the level of interest in the corresponding discussion topics. Owing to this, the administrators of the services have the opportunity to organize and plan further work of the application, both in terms of expanding the range of topics and improving the functionality and user experience of the proposed web application of the forum.

A feature of the application of the proposed web forum in the future will be the use of the model *Software as a Service* (Saas) [19], which will allow providing software in the format of a service. Within the framework of this model, it will be possible to use the forum builder as a platform on which the users will have access to powerful tools for creating and managing posts, that is, they will be able to configure their own forums, adjust their functionality, design and adapt them to personal needs.

CONCLUSIONS

A mathematical model of the web forum was built, and the application was implemented using modern approaches to software development using the optimized MVC architecture, which enabled simplification of creating a service by distributing responsibilities between the application modules and facilitating testing and technical support of the service.

As a result of the analysis of well-known analogues, the requirements for the software implementation were determined and the main aspects of own development were formulated, which has convenient functionality, high reliability and meets the modern needs and requests of users.

The scientific novelty is the development of a method for evaluating the usefulness of discussions in a web forum based on the introduction of a new informative quality parameter, the use of which allowed broadening the scope of existing limitations in quantitative analytics of discussions and feedbacks in popular services.

The *h*-index was further used to evaluate the interest of users in the topics of discussions on the web forum.

An experimental verification of the use of the service in the educational process of the Precarpathian National University was carried out by evaluating the parameter of the usefulness of discussions, which enabled significant diversification of educational activities, increasing the level of practical training for students and improving the exchange and discussion of relevant programmatic and scientific issues for both teachers and the student community.

The practical significance of the obtained results is the development of a virtual educational tool, which enables

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improving the quality of the provision of educational services in a higher education institution.

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МЕТОД ВИЗНАЧЕННЯ ПАРАМЕТРА ЯКІСНОЇ ОЦІНКИ ВЕБ-ФОРУМУ

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АНОТАЦІЯ

Актуальність. Розробка нових типів віртуальних середовищ є актуальною задачею інформатизації сучасної освіти, оскільки подібні сервіси дозволяють якісно підвищити рівень надання освітніх послуг та сприяють більш глибшому засвоєнню нових знань студентами. Запропонований в роботі веб-застосунок побудований з використанням сучасних підходів створення веб-сторінок за допомогою мови програмування .NET, фреймворків Bootstrap і ASP.NET MVC, хмарних рішень Azure та баз даних Azure SQL, що дозволило спростити розробку програмного забезпечення шляхом розподілу функцій між модулями програми та забезпечило гнучкість, продуктивність та безпеку, необхідну для роботи з реляційними даними. Ефе-

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ктивність застосування у навчальному процесі експериментально перевірено із застосуванням методу визначення якісної оцінки параметра корисності веб-форуму, який розроблений за рахунок введення інформативного параметра якості дискусії на основі використання індексу Гірша.

Мета. Побудова математичної моделі веб-форуму та розробка методу визначення якісної оцінки параметра корисності дискусій у створеному веб-застосунку, що дозволило підвищити якість проведення освітньої і наукової діяльності у закладі вищої освіти.

Метод. Розроблено метод визначення параметра якісної оцінки веб-форуму з використанням індексу Гірша, що дало можливість виконати аналіз зацікавленості висвітлення напрямків обговорень на сторінках форуму та на його основі проводити планування подальшої роботи форуму як інструменту віртуального навчального середовища.

Результати. На основі аналізу результатів впровадження веб-застосунку в навчальний процес кафедри інформаційних технологій Прикарпатського національного університету імені В. Стефаника виконано аналітику користувацької активності дописів та за рахунок введеного параметра активності визначено ефективність дискусій запропонованих тем на сторінках форуму.

Висновки. В даному дослідженні виконано побудову математичної моделі веб-форуму та програмно реалізовано застосунок із використанням сучасних підходів до розробки програмного забезпечення за допомогою оптимізованої архітектури MVC, що дозволило спростити процес створення сервісу шляхом розподілу обов'язків між модулями програми та полегшити тестування і підтримку сервісу.

Наукова новизна полягає в розробці методу оцінки корисності дискусій у веб-форумі за рахунок введення нового інформативного параметра якості, використання якого дозволило розширити обмеження щодо кількісної аналітики обговорень та відгуків у відомих сервісах. Експериментальні дослідження, проведені на базі закладу вищої освіти, підтвердили ефективність його застосування для підвищення якості надання освітніх послуг. Практичне значення отриманих результатів полягає в розробці програмного продукту як інструменту віртуального навчального середовища вузу.

КЛЮЧОВІ СЛОВА: віртуальне середовище, веб-форум, математична модель, хмарні технології, параметр активності, метод якісної оцінки веб-форуму.

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COST OPTIMIZATION METHOD FOR INFORMATIONAL INFRASTRUCTURE DEPLOYMENT IN STATIC MULTI-CLOUD ENVIRONMENT

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ABSTRACT

Context. In recent years, the topic of deploying informational infrastructure in a multi-cloud environment has gained popularity. This is because a multi-cloud environment provides the ability to leverage the unique services of cloud providers without the need to deploy all infrastructure components inside them. Therefore, all available services across different cloud providers could be used to build up information infrastructure. Also, multi-cloud offers versatility in selecting different pricing policies for services across different cloud providers. However, as the number of available cloud service providers increases, the complexity of building a cost-optimized deployment plan for informational infrastructure also increases.

Objective. The purpose of this paper is to optimize the operating costs of information infrastructure while leveraging the service prices of multiple cloud service providers.

Method. This article presents a novel cost optimization method for informational infrastructure deployment in a static multi-cloud environment whose goal is to minimize the hourly cost of infrastructure utilization. A genetic algorithm was used to solve this problem. Different penalty functions for the genetic algorithm were considered. Also, a novel parameter optimization method is proposed for selecting the parameters of the penalty function.

Results. A series of experiments were conducted to compare the results of different penalty functions. The results demonstrated that the penalty function with the proposed parameter selection method, in comparison to other penalty functions, on average found the best solution that was 8.933% better and took 18.6% less time to find such a solution. These results showed that the proposed parameter selection method allows for efficient exploration of both feasible and infeasible regions.

Conclusion. A novel cost optimization method for informational infrastructure deployment in a static multi-cloud environment is proposed. However, despite the effectiveness of the proposed method, it can be further improved. In particular, it is necessary to consider the possibility of involving scalable instances for informational infrastructure deployment.

KEYWORDS: cost optimization, information infrastructure, initial placement, multi-cloud, parameters selection method, penalty function.

ABBREVIATIONS

VM is a virtual machine;

GA is a genetic algorithm;

AWS is an Amazon web services;

vCPU is a virtual central unit processor.

NOMENCLATURE

P is a set of cloud service providers;

G is a set of virtual machines with general-purpose specialization that are available in all cloud service providers P;

A is a set of application components which define information infrastructure;

S is a relation matrix ($A \times A$) of application components that must be deployed within the same cloud provider;

D is a relation matrix ($A \times A$) of application components that should be placed in different clouds;

R is a set of availability zones, that are available in all cloud providers P;

B_{ra} is a relationship matrix ($R \times A$) which defines the possibility of deploying application component $a \in A$ in availability zone $r \in R$.

C_{prg} is a hourly price of on-demand usage of a virtual machine at the provider $p \in P$, in the region $r \in R$ of class $g \in G$.

X_{aprg} is a binary decision variable equal to 1 when component $a \in A$ is placed at the provider $p \in P$, in the region $r \in R$, of the VM class $g \in G$, and 0 otherwise;

W_{pg} is a number of CPU cores of virtual machine type $g \in G$ from the cloud provider $p \in P$;

$W_a^{\min}$ is a minimum required number of CPU cores for application component $a \in A$;

E_{pg} is a amount of memory of virtual machine type $g \in G$ from the cloud provider $p \in P$;

$E_a^{\min}$ is a minimum required amount of memory for the application component $a \in A$;

s is a number of constraints that have been met;

m is a total number of constraints;

r_i is a penalty weight multiplier that inequity constraints impose when violated;

c_j is a penalty weight multiplier that equity constraints impose when violated.

INTRODUCTION

Cloud computing gained popularity in the last decade and continues to be relevant in our time [1]. Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., servers, storage, applications, services, and networks) that can be rapidly provisioned and released with minimal management effort

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or service provider interaction [2]. The significant advantage of using the cloud provider’s services is the ability to rapidly scale infrastructure components. This advantage is achieved due to the rapid provision of additional computing services for a certain period, which allows to overcome spikes in service demand. This makes cloud computing superior to on-premise solutions, as their computing resources cannot scale with the same ease and speed.

In turn, the combination of on-premise data centers and services of cloud providers is widely used in the industry for hosting information infrastructure. This approach is called a hybrid cloud. In such an approach, the services of cloud providers are often used to handle high demand, while the main computational resources are concentrated in on-premise data centers. However, while this approach solves the problem of limited scalability of on-premise data centers, it is not a long-term solution because on-premise data centers require constant support and updates.

According to statistics for 2023, about 92% of companies plan or already stick to a multi-cloud approach for service deployment [3, 4]. This statistic is primarily associated with the advantages provided by a multi-cloud in comparison to the use of a single-cloud provider. The biggest disadvantage of using the services of only one provider is the problem of vendor lock. Vendor lock refers to a situation where an organization becomes heavily dependent on a specific cloud service provider. This dependency restricts the ability to switch to another cloud provider without spending a substantial budget. The multi-cloud offers greater flexibility in service deployment, as all availability zones of selected cloud service providers can be used to deploy services. As shown in statistics [3], one of the main reasons for using a multi-cloud approach is cost optimization for service deployment and utilization. This is because multi-cloud provides access to different pricing policies for identical services among different cloud providers. For example, a virtual machine with 4 virtual processors and 16 gigabytes of RAM in the geographical area of Tokyo costs $0.2502 per hour of usage in AWS [5], compared to Google Cloud where a virtual machine with the same characteristics costs $0.2168 per hour of usage [6].

Despite the significant advantages provided by the multi-cloud, it also introduces additional complexity in building an information infrastructure deployment plan. Such complexity is associated with an increased set of possible options, across different providers. The dynamic changes in load and virtual machine price also add significant complexity during deployment plan construction. To overcome these problems, cloud service brokering mechanisms are often used [7]. In general, such mechanisms accept as input parameters the initial deployment plan of services and statistical data regarding load changes over a certain period. However, while the user can provide reliable information regarding the service placement of information infrastructure, collecting and presenting information about the dynamics of service load changes can be problematic. The main problem in providing such information lies in its collection. In order to collect data about the load, it is necessary to observe the operation of the services, which involves additional costs. Another problem is that by the time the data is transferred to the broker, it will already be out of date.

To address the identified problems, this study will propose a cost optimization method for information infrastructure deployment in a static multi-cloud environment. A static environment was chosen because the information infrastructure will be deployed to collect data on service loads and obtain patterns of their use. That is, it is assumed that the data collection period will be shorter than the period of updating prices for service usage by the cloud service provider. Information collected in this way will reflect the actual system needs. In the future, this information could be used by the broker for dynamic infrastructure component placement. Additionally, the resulting initial placement strategy can speed up the dynamic placement algorithm by using the provided initial deployment plan as a starting point in the algorithm’s operation.

The object of study is the informational infrastructure deployment in a static multi-cloud environment. This involves analysing how different service pricing for comparable services from different cloud service providers can be utilized to minimize the cost of informational infrastructure operation.

The subject of study is the methods of combinatorial optimization for creating an information infrastructure deployment plan.

The purpose of the work is to develop a method which will create a deployment plan for informational infrastructure in a static multi-cloud environment. The resulting plan should consider the provided constraints on virtual machine parameters and placement strategy. The goal is to minimize the hourly operational cost of infrastructure utilization.

1 PROBLEM STATEMENT

Suppose that the hourly price for the use of virtual machines of class $g \in G$, across cloud providers $p \in P$, within availability zones $r \in R$ is static and set to C_{prg}. Also, provided a set of application components $a \in A$ that form informational infrastructure, which should be deployed. Then, the set of decision variables X_{aprg} should be found that will minimize the information infrastructure deployment cost as presented in (1–7).

$$\min \sum_{a\in A}\sum_{p\in P}\sum_{r\in R}\sum_{g\in G} C_{prg} X_{aprg}, \quad (1)$$

Subject to:

$$\sum_{p\in P}\sum_{r\in R}\sum_{g\in G} X_{aprg} W_{pg} \geq W_a^{\min}, \forall a \in A, \quad (2)$$

$$\sum_{p\in P}\sum_{r\in R}\sum_{g\in G} X_{aprg} E_{pg} \geq E_a^{\min}, \forall a \in A, \quad (3)$$

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$$\sum_{p\in P}(\sum_{r\in R}\sum_{g\in G}X_{a_1prg}\times\sum_{r\in R}\sum_{g\in G}X_{a_2prg})\ge S_{a_1a_2}, \quad (4)$$

$$\forall a_1\ne a_2, a_1,a_2\in A,$$

$$\sum_{p\in P}(\sum_{r\in R}\sum_{g\in G}X_{a_1prg}\times\sum_{r\in R}\sum_{g\in G}X_{a_2prg})\le D_{a_1a_2}, \quad (5)$$

$$\forall a_1\ne a_2, a_1,a_2\in A,$$

$$\sum_{p\in P}\sum_{g\in G}X_{aprg}\le B_{ra}, \quad \forall a\in A, \forall r\in R, \quad (6)$$

$$\sum_{p\in P}\sum_{r\in R}\sum_{g\in G}X_{aprg}=1, \quad \forall a\in A, \quad (7)$$

$$X_{arpg}, D_{a_1a_2}, S_{a_1a_2}, B_{ra}\in N_0,$$

$$C_{rpg}, W_a^{\min}, E_a^{\min}, E_{pg}, W_{pg}\in N.$$

Where (2) and (3) define the constraints regarding the virtual machine parameters on which the application component should be deployed. Where (2) describes the constraint for the minimal number of virtual cores and (3) describes constraints regarding the minimal amount of virtual memory. Constraints (4) specifies application components that must be deployed within the same cloud provider, while (5) specifies the components that must be deployed in different cloud providers. In (6) the constraints regarding deploying application components only in certain availability zones are described. Constraint (7) specifies that each application component must be deployed only in one instance on one of the available virtual machines. This limitation is introduced to simplify the gathering of necessary information.

2 REVIEW OF THE LITERATURE

The topic of virtual infrastructure deployment, or Virtual Machines (VMs) placement problem, is widely described in the literature. These problems are often classified as combinatorial problems. The main approach to solving these problems is mathematical optimization methods. In the literature, the VMs placement problem is reviewed from two perspectives: from the cloud service provider's perspective and from the cloud resource consumer's perspective.

The main goal of a cloud service provider is to maximize profit by utilizing existing resources. For instance, increasing the profit of the cloud provider in [8] is achieved by minimizing electricity consumption by the data centers. This is achieved by compactly rearranging VMs placement. Meantime the authors tried to find a balance in service level agreement change, simultaneously maximizing it. Additionally, cost optimization can be achieved through network traffic optimization by reducing the distance between servers, as demonstrated in [9].

On the other hand, the goal of cloud service consumers is to minimize the utilization costs of information infrastructure that is deployed on the cloud provider's services. In articles [7, 10–17], the main focus was concentrated on minimizing costs associated with operating the information infrastructure in the cloud. For example, in [10], the authors formulated the problem of virtual machine placement as a multi-objective optimization problem, the main goal of which was to minimize processing and memory resource usage. As a result, the authors proposed the VMPACS algorithm to solve this problem. The main goal of the proposed algorithm is to search the solution space more efficiently and obtain a Pareto set of solutions.

In recent years, the multi-cloud has increasingly attracted the attention of researchers. This trend is because multi-cloud provides the ability to use different pricing policies that are available among different cloud service providers. This leads to the expansion of search space in solving the problem of cost optimization of information infrastructure utilization in the cloud. Thus, in [11] the authors proposed an algorithm for the optimal placement of applications in a hybrid cloud. The described algorithms specialized in service-based applications (SBA) placement. The authors aimed to optimize the communication and hosting costs of SBA. By striking a balance between private and public cloud resources, the proposed algorithm aims to enhance the overall efficiency of hybrid cloud deployments. In [12], authors proposed an optimal virtual machine placement (OVMP) algorithm. The goal of the presented algorithm is to minimize the cost of hosting VMs in a multi-cloud environment with consideration of the uncertainty of demand and VMs prices. The problem in OVMP is described as a two-stage stochastic integer programming problem. In [13] a novel cloud brokering architecture was presented. This architecture provides a cost-optimized deployment plan for the placement of virtual resources in a multi-cloud environment. The main objective of the resulting deployment plan is to select the best cloud services with optimal cost, considering the value of the defined Service Measurement Index along with additional physical and logical constraints. The proposed cloud brokering architecture has been modeled using a mixed integer programming formulation. This formulation is solved using the Benders decomposition algorithm.

In many studies, the type of VMs placement is divided into static and dynamic. Dynamic placement involves optimization of the existing infrastructure placement plan through dynamic adjustments considering changes in service loads. Articles dedicated to dynamic placement operate with statistical data regarding changes in service prices, service loads, and other parameters. Dynamic placement algorithms are executed once in a certain period to respond to a change in load that occurred since the last algorithm invocation. These algorithms should be fast to make changes in VMs placement plan as quickly as possible to reduce the time gap when the number of available services mismatches the load. In [14], the authors proposed an optimal cloud resource provisioning (OCRP) algorithm to address the challenge of resource provisioning in cloud computing. The authors formulated a stochastic programming model to optimize the provisioning of computing resources. They have used both reservation and on-demand provisioning plans. The

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algorithm takes into account the uncertainty of demand and resource prices. The authors inspected different approaches to obtain the solution of the OCRP algorithm, such as deterministic equivalent formulation, sample-average approximation, and Bender's decomposition algorithm. In [7] authors addressed the Cloud Resource Management Problem in multi-cloud environments. The authors tried to reduce the cost and the execution time of consumer applications among Infrastructure as a Service services from multiple cloud providers. The authors used a Biased Random-Key Genetic Algorithm to solve the problem. This algorithm is based on a cloud brokerage mechanism and is designed to provide high-quality real-time solutions to automate the cloud resource management and deployment process.

Along with dynamic VMs placement algorithms, static VMs placement algorithms are appearing in the literature [15–17]. Unlike dynamic, static placement algorithms are invoked only once to determine the initial infrastructure placement plan. These algorithms are static due to neglecting the dynamic changes of various parameters such as load, service costs, service availabilities, etc. Such neglect occurs since the algorithm uses the available values at the time of invocation, without taking into account their subsequent change over time [15]. The purpose of the infrastructure deployed in such a way is to obtain metrics regarding its operation and interaction patterns. In [15], the authors proposed an architecture for a cloud broker that deploys VMs across multiple clouds. The goal of the broker was to minimize the total infrastructure cost by selecting the best cloud provider services based on the current conditions. The authors presented a binary integer programming formulation of the problem, which was then resolved using AMPL with the use of MINOS and CPLEX solvers. In [16] authors proposed a solution to optimize the placement of VMs across multiple cloud providers taking into account user-provided criteria. The developed algorithm was formulated as an integer programming problem. The authors tried to find a balance between price and performance tradeoffs for the resulting placement plan. Criteria provided by the user could steer the VM allocation by specifying the maximum budget along with minimum acceptable performance value along with constraints regarding load balance, hardware configuration of individual VMs, etc. In [17] authors formulated the problem of cost optimization in a multi-site multi-cloud environment. Optimization criteria were considered as the total price of infrastructure deployment which included the price of VMs reservation and the price of communication between them. To solve the problem authors formulated a greedy-based algorithm.

In reviewed articles, the VMs placement problem is carried out, almost without consideration of dependency between them. As some articles include data transmission cost into the total cost, it is not enough to describe dependency and communication between applications inside information infrastructure. Also, the described approaches consider that distinct applications in informational infrastructure should be placed within one virtual machine. Such a model does not reflect modern trends. Nowadays, with the development of architectural approaches to building informational infrastructure, the virtual machine is used to host application component rather than the whole application. Additionally, most of the reviewed articles ignore the possibility of deploying information infrastructure components in different availability zones. Therefore, they are using a multi-cloud approach only to expand the possible choice of VMs for placement. In contrast, this work will propose a method for information infrastructure deployment in a static multi-cloud environment, in which application components are placed on different VMs. Also, the possibility of deploying infrastructure components in different availability zones will be considered, as well as the constraints regarding service placement in certain availability zones that are associated with the legislation of different countries.

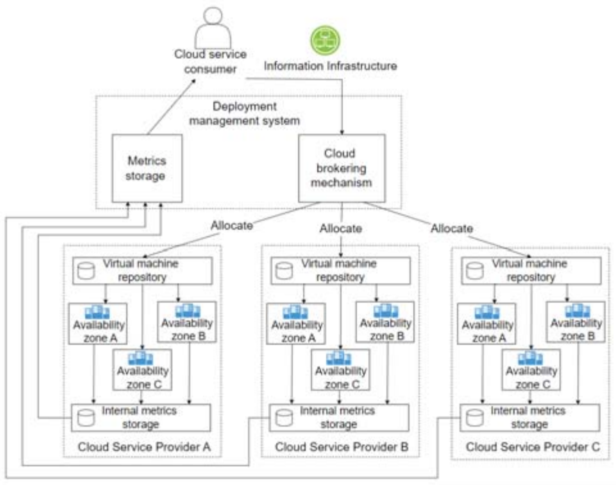

Figure 1 – System model

3 MATERIALS AND METHODS

As depicted in Figure 1, the system model consists of six core components: cloud service consumer, cloud service provider, virtual machines, information infrastructure, availability zones of cloud providers, and cloud brokering mechanism. The cloud service consumer wants to deploy information infrastructure.

Cloud service providers specialize in providing cloud services to customers on demand. Cloud service providers offer the following service models: Software as Service (SaaS) – the capability provided to the consumer to use the provider's applications running on cloud infrastructure, Infrastructure as Service (IaaS) – the capability provided to the consumer to provision processing, storage, networks, and other fundamental computing resources where the consumer can deploy and run arbitrary software, which can include operating systems and applications, Platform as Service (PaaS) – the capability provided to the consumer to deploy onto the cloud infrastructure consumer-created or acquired applications created using programming languages,

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libraries, services, and tools supported by the provider [2]. Let $P = \{P_1, P_2, ..., P_{last}\}$ define the set of cloud service providers.

Cloud service providers offer non-standardized APIs for interacting with their services. Such makes those services not interchangeable among different providers. Consequently, the only model that has unified characteristics and configuration parameters, regardless of the selected cloud service provider is application-level services, specifically IaaS services. In this work, among all IaaS services, the deployment of virtual machines will be reviewed.

The virtual machines within each cloud provider are divided into classes by specialization in such a way that they fully cover customers' needs. Within each specialization, virtual machines are further divided into classes. The division into classes is based on the virtual machine parameters, with the most common criteria being the number of virtual processors and the amount of virtual memory. Thus, among cloud service providers, analogs can be found for each type of virtual machine within each specialization. This work will focus on virtual machines with general-purpose specialization. General-purpose virtual machines provide a balance of computing, memory, and networking resources. These instances are ideal for applications that use these resources in equal proportions, such as web servers [18]. Therefore, let $G = \{G_1, G_2, ..., G_{last}\}$ define a set of virtual machine classes within general-purpose specialization that are available among all providers.

Nowadays, there is no direct correlation between the set of applications in the information infrastructure and the resulting number of virtual machines that will be used for their deployment. This is associated with the use of new architectural approaches to building information infrastructure and its components. An example of such an architecture is service-oriented architecture (SOA) [19]. In this architecture applications can be divided into several components, each of which can be separately deployed on different virtual machines. Such a deployment approach enables independent scaling of application components which leads to more efficient resource utilization. Let $A = \{A_1, A_2, ..., A_{last}\}$ define the set of application components. Set A allows the deployment of different applications and therefore their components, to do so all application components of all applications should be placed inside the set.

During the application operation, its components constantly exchange requests and messages, generating a significant data flow. To optimize the cost of information infrastructure operation, application components are placed as close as possible to each other, usually within the same provider. Such placement occurs because most cloud providers have zero communication costs within the internal network, unlike the costs for communication with external networks [20]. Therefore, let S $(A \times A)$ define the relation matrix of application components that must be deployed within the same cloud provider. Thus, $S_{a_1a_2}$ equals 1 when a_1 and a_2 components must be deployed within the same provider, and 0 otherwise.

Despite the benefits of services co-location, it is also associated with certain risks. The article [21] gives examples in which, in order to ensure system security, application components are deployed on separate clouds. Such fragmentation of the application is associated with mistrust towards cloud service providers, as they represent a closed system where it is impossible to track what happens to the application source code that is transferred for hosting. Cloud service providers have access to inbound and outbound application traffic. Using this data, application logic can be reconstructed. Due to such risks, some architectural approaches divide the application into components, so that the information about each component is insufficient to reconstruct an overall picture of the application's operation. Moreover, these components are deployed on different clouds. Therefore, let D $(A \times A)$ define the relationship matrix of application components that should be placed in different clouds. Thus, $D_{a_1a_2}$ equals 0 when a_1 and a_2 components must be deployed in different providers, and 1 otherwise.

However not only safety considerations can make adjustments to the service deployment plan. Restrictions regarding service deployment may arise from the legislation of the country in where the user operates. Also, similar restrictions may arise for clients with whom the user operates. These restrictions are often related to regional zones where data can be stored and how it should be used, along with who can access it, and under which conditions. An example of such a restriction is the General Data Protection Regulation (GDPR). GDPR in the European Union imposes restrictions on the transfer of personal data outside the European Economic Area (EEA) to ensure an adequate level of protection. Data transfers to countries outside the EEA must adhere to specific safeguards outlined in the GDPR, such as adequacy decisions, standard contractual clauses, binding corporate rules, or explicit consent from data subjects [22]. In the United States, similar restrictions are imposed by laws such as HIPAA [23] and GLBA [24]. Additionally, countries such as China, Indonesia, Vietnam, and India have restrictions in which certain types of data should be stored and processed only within the country. Therefore, let $R = \{R_1, R_2, ..., R_{last}\}$ define the set of availability zones, such that each provider $p \in P$ has a data center located in the availability zone $r \in R$. Also, let B $(R \times A)$ define the relationship matrix between application component a and availability zone r. Such that, B_{ra} equals 0 when component a should not be deployed in the availability zone r, and 1 otherwise.

Cloud service providers offer access to resources on-demand basis, charging an hourly fee for their usage. The cost of using a virtual machine depends on its specialization, parameters, and the region in which it will be deployed. In addition to the on-demand plan, cloud service providers offer the opportunity to reserve virtual machines for a long period. In the reservation plan, the user pays an upfront fee along with an hourly usage fee.

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The hourly cost of using a reserved virtual machine is lower than the on-demand rate [25].

This study focuses on the initial deployment of infrastructure in a multi-cloud environment, the main purpose of which is to collect the necessary metrics for further infrastructure utilization. It is considered that the observation period will be less than the minimum reservation period, i.e., one year, so only on-demand virtual machines will be used. Also, such a pricing scheme is appropriate given the uncertainty of the virtual machines' utilization post-observation period. Therefore, let the element C_{prg} from the matrix C ($P \times R \times G$) define the hourly price of a virtual machine at the provider $p \in P$, in the region $r \in R$ of class $g \in G$ for on-demand usage.

The described problem is a combinatorial optimization problem, as the main challenge lies in the optimal or suboptimal deployment of virtual machines. Combinatorial optimization problems (COPs), especially real-world COPs, are challenging because they are difficult to formulate and solve. Additionally, choosing the proper solver algorithm and defining its best configuration is also a difficult task due to the existence of several solvers characterized by different parametrizations [26].

To solve the problem, a family of genetic algorithms was used. Genetic algorithms (GA) are a family of computational models inspired by evolution. These algorithms encode a potential solution to a specific problem on a simple chromosome-like data structure and apply recombination operators to these structures to preserve critical information [27]. The general scheme of the GA is presented in Figure 2.

```
Algorithm 1 Genetic algorithm
Initialize the initial population P randomly
Set the generation counter g = 0
while the termination criterion is not met do
    Evaluate the objective function values for each individual in P
    Calculate the fitness value for each individual based on the objective
function results
    Increment the generation counter (g += 1)
    Select individuals for reproduction based on fitness values
    Apply the crossover operation to generate offspring
    Apply the mutation operation to introduce variations
    Update population P with the new generation of individuals
end while
return the individual with the lowest objective function value from P
```

Figure 2 – General scheme of generic algorithm

Due to constraint (7), the solution string encoding is performed in the form of representing decision variables as a vector.

GA is suited for unconstrained optimization. For use in constrained optimization, a penalty function is introduced. The main goal of the penalty function is to add a penalty value to the fitness result for an infeasible solution. The penalty value depends on the constraint's violation amount or on the amount by which constraints are violated. Therefore, a feasible result would have more chances to pass through during the reproduction phase in comparison to an infeasible one. There are two types of penalty functions: exterior and interior [27]. In the interior penalty function, all elements from the initial population should be feasible. On the other hand, the exterior penalty function doesn't require an initial population to be feasible. Exterior penalty functions are used more often because, in some cases, finding a feasible solution is itself an NP-hard task.

In this work, different exterior penalty functions will be compared to find out the best-fitting one for the described problem, such as:

– Static penalty function;
– Dynamic penalty function;
– Additive penalty function.

The static penalty function adds a penalty based on the number of violated constraints. The static penalty function was taken from [28] and has the following form:

$$static\ (x) = \begin{cases} of\,(x), & \text{when } x \text{ is feasible,} \\ K(1 - \frac{s}{m}), & \text{otherwise.} \end{cases} \qquad (8)$$

Where x is the solution vector, $of\,(x)$ is the value of the objective function for the solution vector x, K is a large positive constant, s determines the number of constraints that have been met, and m determines the total number of constraints.

A dynamic penalty function adjusts the penalty value during the optimization process using information about the current state of the population. These adjustments balance the exploration and exploitation phases of optimization, potentially improving both the speed and quality of results. The dynamic penalty function was chosen from [29] and presented in equations (9–12):

$$dynamic\ (x) = of\,(x) + (Yt)^{\alpha}\, SVC(\beta, x)\,, \qquad (9)$$

$$SVC(\beta, x) = \sum_{i}^{q} D_i^{\beta}(x) + \sum_{j=q+1}^{m} D_j(x)\,, \qquad (10)$$

$$D_i(x) = \begin{cases} 0, & \text{when } g_i(x) \le 0,\ i \le q, \\ |g_i(x)|, & \text{otherwise,} \end{cases} \qquad (11)$$

Where in (9) x is the solution vector, $of\,(x)$ is the value of the objective function for the solution vector x. Y, α, β are the input parameters of the penalty function, which are defined by the user and t is the iteration counter. Equation (10) determines the value of the penalty function depending on the violated constraints, where m is the total number of constraints. The (11) equation determines the penalty value imposed by inequality constraints when the constraints are violated, suppose that inequality constraints have the following representation $g_i(x) \le 0$, $\forall\, i \in \{1, 2, \ldots, q\}$. The (12) equation in turn determines the penalty value for equality constraints with following form $h_j(x) = 0$, $\forall\, j \in \{q+1, q+2, \ldots, m\}$.

The additive penalty function uses weights that are defined for each constraint independently. Additive penalties have the following form:

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$$additive\ (x) = of\,(x) + \sum_{i}^{q} r_i G_i(x) + \sum_{j=q+1}^{m} c_j L_j(x), \tag{13}$$

$$r_i \in M \quad \forall i \in \{1, 2, ..., q\}, \;\; c_j \in M \;\; \forall j \in \{q+1, q+2, ..., m\}$$

$$G_i(x) = \max[0, g_i(x)^{\beta}], \tag{14}$$

$$L_j(x) = |h_j(x)|^{\gamma}. \tag{15}$$

Where in (13) r_i and c_j define the penalty weight multipliers that inequality and equality constraints respectively impose when violated. Also, parameters β and γ in (14) and (15) are used to balance the impact that inequality and equality constraints have on penalty value. The set *M* contains the values of all weights. Compared to the previously described penalty functions, this function can be more precisely adapted to the problem due to a larger set of parameters and the possibility of fine-tuning them. But with such an opportunity, the problem of finding the values of these weights arises. The issue is that the penalty value directly depends on the values of the weights r_i and c_j. If they are set too small, the time to find the first feasible solution will increase, while the result could be better due to the possible search across the infeasible region [28]. Conversely, if r_i and c_j are given too large values, the GA will quickly enter the local optimum and will less frequently resort to searching across infeasible space.

To find the r_i and c_j parameter values of the additive function, the scalable semi-swarm parameter optimization algorithm (S3POA) was developed. The algorithm consists of two stages: finding relative parameter values and adjusting them.

In the first stage of the S3POA algorithm, the objective function was modified so that each constraint, when violated, was multiplied by a large value. Thus, the penalty function takes the following form (16).

$$Evaluate\ (x) = of\,(x) + B\left[\sum_{i}^{q} \tilde{r}_i G_i(x) + \sum_{j=q+1}^{m} \tilde{c}_j L_j(x)\right]. \tag{16}$$

Algorithm 2 Scalable Semi-Swarm Parameter Optimization Algorithm (S3POA)

```
Input: geneticAlgorithmIterationCount, S3poaIterationCount
Output: M̃
Initialize M̃ as an array of 1s with the length of m
Set i = 0
while i < S3poaIterationCount do
    Set the iteration count for the genetic algorithm to geneticAlgorithmIterationCount
    Set constraint weights to M̃
    last_population = run the genetic algorithm with the given parameters
    if any element in last_population is not feasible then
        most_violated = get the most violated constraint from last_population
        Increment the element in M̃ corresponding to most_violated
    end if
    i += 1
end while
return M̃
```

Figure 3 – Scheme of the first stage of S3POA

In Figure 3 the scheme of the first stage of S3POA is presented. The input parameters for the described algorithm include the number of iterations of the GA. This value should not be too small to allow the algorithm to reach a local optimum, but it also should not be too big to prevent the algorithm from conducting a long search in the infeasible region. The idea of the first stage algorithm involves conducting a fixed number of iterations of the GA with the (16) objective function. After the GA is finished, the final population is analyzed. If any element of the final population belongs to the feasible region, the next iteration of the algorithm is performed. Otherwise, among the elements of the final population, the constraint with the most violations is identified. After finding such a constraint, its corresponding relative weight ($\check{r}_i$ for a non-strict constraint and $\check{c}_j$ for a strict constraint) is increased by one. The next iteration of the algorithm is conducted with updated weights. The algorithms continue until a given number of iterations is reached which is provided as an input parameter to the algorithm.

Gradually increasing the values of the stopping weights, decreases the probability that they will be violated in the next iteration of the algorithm. This leads to a more comprehensive consideration of the resulting weight values. As a result, the values of the relative weights $\check{r}_i$ and $\check{c}_j$ are obtained such that $\check{r}_i \in \tilde{M}\ \forall\, i \in \{1, 2, \ldots, q\}$, $\check{c}_j \in \tilde{M}\ \forall\, j \in \{q+1, q+2, \ldots, m\}$. These relative weights allow for examining the relationship between constraints.

The found relative weight values cannot be used immediately to solve the given problem, as their value increases with the number of algorithm iterations, which may result in assigning excessive values to them. Excessively large values of these parameters will lead to a situation where the GA will quickly find a feasible solution, but then it will have a harder time considering infeasible solutions because it will have excessively high fitness values [28]. To overcome this issue, found weight values are considered relative. To find the best fitting weight values, the objective function from (13) will be used, but with the following values:

$$r_i = \begin{cases} 1, & \check{r}_i = 1, \\ \mu \check{r}_i, & \text{otherwise}, \end{cases} \tag{17}$$

$$c_j = \begin{cases} 1, & \check{c}_j = 1, \\ \mu \check{c}_j, & \text{otherwise}. \end{cases} \tag{18}$$

In (17) and (18), the multiplier μ is responsible for the scale that should be applied to the variables $\check{r}_i$ and $\check{c}_j$ to avoid the problem of insufficient and excessive weight assignment. The value of relative weights equal to 1 is not scaled since during the experiments these constraints were not violated, so they do not prevent reaching the feasible solution.

4 EXPERIMENTS

To conduct the experiments, the input parameters of the problem were set and presented in Tables 1 – 6. Table 1 shows the regions where virtual machines will be

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deployed. As for cloud service providers, AWS, Azure, and Google Cloud were chosen as they occupy a significant portion of the cloud services market [30].

Table 1 – Correspondence of the geographic regions to the availability regions of the providers

	AWS	Azure	Google Cloud
EU west	eu-west-1	West Europe	europe-west1-b
US east	us-east-1	East US	us-east4-a
EU central	eu-central-1	Sweden Central	europe-north1-a
Japan	asia-south1-a	Japan East	asia-northeast1-a

Table 2 – Description of selected virtual machines among different cloud service providers

VM names	Provider	vCPUs	Memory Size (GB)	Price in West Europe ($)	Price in East US ($)	Price in North Europe ($)	Price in Japan ($)
t2.small	AWS	1	2	0.027	0.025	0.0286	0.0322
t2.medium	AWS	2	4	0.0539	0.0499	0.0571	0.0643
t2.xlarge	AWS	4	16	0.2086	0.1926	0.2214	0.2502
t2.2xlarge	AWS	8	32	0.4172	0.3852	0.4428	0.5004
Standart_A1_V2	Azure	1	2	0.041	0.043	0.041	0.054
Standart_A2_V2	Azure	2	4	0.087	0.091	0.0861	0.113
Standart_A4_V2	Azure	4	8	0.183	0.191	0.182	0.238
Standart_A8_V2	Azure	8	16	0.383	0.4	0.38	0.5
t2d-standard-1	Google Cloud	1	4	0.0465	0.0476	0.0465	0.0542
t2d-standard-2	Google Cloud	2	8	0.0929	0.0952	0.093	0.1084
t2d-standard-4	Google Cloud	4	16	0.1859	0.1903	0.1861	0.2168
t2d-standard-8	Google Cloud	8	32	0.3718	0.3806	0.3721	0.4336

Information about the selected classes of virtual machines, their characteristics, and the on-demand hourly cost of using them relative to regions is presented in Table 2. According to the information presented in Table 2, four different classes of virtual machines were formed based on the number of virtual processors. Tables 3–5 describe the requirements regarding application components deployment. Thus, Table 3 presents the requirements regarding application components deployment within the same cloud service provider, defining the matrix *S*. Table 4 presents the requirements regarding application components deployment within different cloud service providers, defining the matrix *D*. Table 5 describes the requirements regarding the characteristics of virtual machines on which application components should be deployed.

Constraints regarding the application components deployment in relation to availability zones were also introduced. Specifically, a_3 and a_6 application components must be located within the European geographic region, meaning they can be deployed in the EU West and EU Central geographical zones.

Table 3 – Constraints on the placement of application components within one provider

	1	2	3	4	5	6	7	8
1	0	1	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0
3	0	0	0	0	0	1	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	1	0	0	0	0	0
7	0	0	0	0	0	0	0	1
8	0	0	0	0	0	0	1	0

Table 4 – Constraints on the placement of application components across different providers

	1	2	3	4	5	6	7	8
1	1	1	0	1	1	0	1	1
2	1	1	0	1	1	0	1	1
3	0	0	1	1	1	1	0	0
4	1	1	1	1	0	1	1	1
5	1	1	1	0	1	1	1	1
6	0	0	1	1	1	1	0	0
7	1	1	0	1	1	0	1	1
8	1	1	0	1	1	0	1	1

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Table 5 – Minimum required virtual machine parameter values for application components deployment

Application	1	2	3	4	5	6	7	8
Min vCPU	2	1	4	6	3	1	2	8
Min Memory (GB)	4	2	16	16	8	2	16	20

To conduct experiments, a virtual machine of class c7i.xlarge from the AWS provider was used. The c7i.xlarge is the compute-optimized family of instances with 4 vCPUs of Intel Xeon Scalable (Sapphire Rapids) with 3.2 GHz clock speed, 8.0 GB of memory, and up to 12.5 Gbps of bandwidth [31].

The same basic parameters of the GA were set for each penalty function. Also, the GA was run 100 times with each penalty function. The termination condition for the algorithm was reaching 1000 iterations.

Parameter tuning of the penalty function parameters as well as other GA parameters is carried out individually for each problem. Parameter tuning for GAs is widely covered in the literature. In this section, the focus will be on parameter tuning for the described penalty functions.

As for the static penalty function input parameter is *K*, which, as described in [29], should be a large number. Therefore, during the experiments, the value determined by the authors will be used, such that $K = 10^9$.

For the dynamic penalty function, the input parameters are the values *Y*, α, β. The authors in [29] suggest using values $Y = 0.5$, $\alpha = 2$, $\beta = 2$. To find the values of these parameters, a series of experiments were conducted, as a result of which it was found that, for the described problem, the best result was achieved with the values $Y = 0.7$, $\alpha = 1$, $\beta = 1$. These values will be used in further experiments.

For the additive penalty function, weight values were calculated with the S3POA algorithm. As input parameters for the S3POA algorithm, the value of *geneticAlgorithmIterationCount* was set to 89. With this number of iterations, GA reached a feasible solution in 47.8% of invocations, such an indicator showed the ability of the algorithm to find feasible value without conducting an extensive search. The value of *S3poaIterationCount* was set to 1000. The value of *B* was set to 10^9. As depicted in [29], common values of β and γ parameters are 1 or 2. During experiments, those parameters were assigned the following values: $\beta = 1$, $\gamma = 2$, since the described problem has only one type of equality constraint (7) which had a significant impact on the result and was most often violated.

5 RESULTS

Based on the results of the conducted experiments, the static penalty function failed to achieve a result that belongs to the feasible region. This outcome was due to the function definition, as it only considered the number of violated constraints without considering the degree of their violation. Unfortunately, this description was insufficient to guide the algorithm toward a feasible result. Therefore, the results of the static penalty function were excluded from the further experiment results.

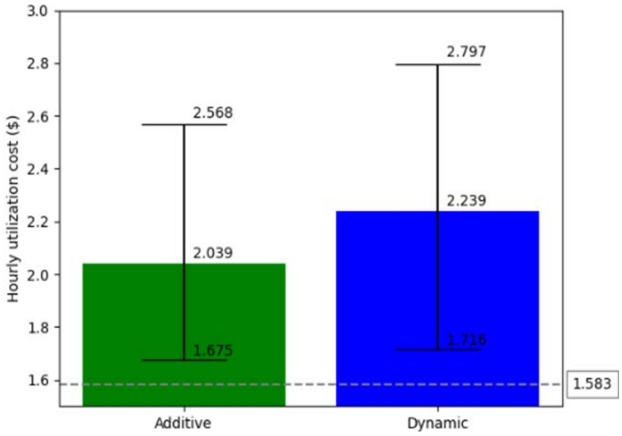

Figure 4 – Comparison of the average objective function values for the additive and dynamic penalty functions.

For the dynamic and additive penalty functions, the resulting values of the objective functions that belonged to the feasible region were compared. To analyze the obtained results, the value of the approximated global optimum was determined. This value was found during problem-solving without considering constraints (4)–(7). The excluded constraints described the deployment plan of virtual machines. Figure 4 demonstrates a comparison diagram of the average obtained results for the dynamic and additive penalty functions. It includes the average, maximum, and minimum values of the objective function obtained during the experiments. The value of the approximated optimum was displayed in Figure 4 with a dashed line.

Additionally, a comparison of the average time spent to find the first feasible and resulting solutions for the dynamic and additive penalty functions was conducted, and the obtained results are presented in Figure 5.

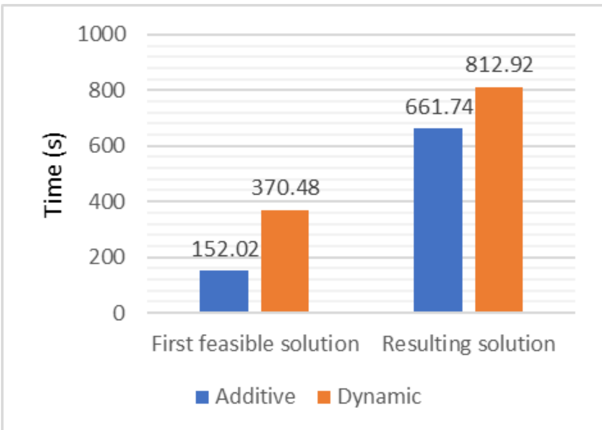

Figure 5 – Comparison of the average time spent to find the first feasible and the resulting solutions for the additive and dynamic penalty functions.

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6 DISCUSSION

Comparing the results of the dynamic and additive penalty functions, it can be concluded that the dynamic penalty function failed to achieve any feasible result in 33% of epy experiments, while for the additive penalty function, this indicator was only 10% of the conducted experiments.

To assess the possibility of the selected penalty functions exiting from the local optimum and continuing searching for a better solution, after reaching the first feasible solution, experiments were conducted in which the first founded feasible solution was compared with the resulting solution of the algorithm. Thus, among all the results that reached a feasible solution, the additive penalty function obtained a resulting solution that was better than the first feasible solution in 85% of cases, while for the dynamic penalty function, this indicator was 61%.

Analyzing Figure 4, it can be concluded that the additive penalty function, on average, showed on 8.933% better results than the dynamic function. Also, on average, the result of the additive function was by 22.36% greater than the value of the approximated optimum.

For the additive penalty function, the average algorithm runtime was 1241.53 seconds, while for the dynamic penalty function, this value was equal to 1239.59 seconds. Based on the obtained results, the use of different penalty functions had almost no effect on the overall algorithm runtime.

Analyzing the data presented in Figure 5, it can be concluded that, on average, the GA with the additive penalty function required 2.437 times less time to find the first feasible solution compared to the dynamic penalty function. Also, the average time spent to find the best solution for the additive penalty function was 18.6% less than the time required for the dynamic penalty function to find such a solution. Considering that 85% of the resulting solutions obtained by the additive penalty function were better than the first feasible solution, compared to 61% for the dynamic function, it can be concluded that, despite spending less time to find the best solution, the additive function less often stopped at the local optimum and had a higher chance of finding a more profitable solution.

Summing up, it can be concluded that during the experiments, the additive penalty function performed better than the dynamic and the static penalty functions. Also, this result indicates that the described S3POA parameter tuning algorithm is capable of balancing the input parameter values. On the one hand, the algorithm spends less time finding the first feasible solution, and on the other hand, upon reaching a local optimum, the algorithm retains the ability to search for better solutions among the infeasible region. Referring to [28], these characteristics indicate the selection of best-fitting parameter values for the penalty function. This result was achieved through direct interaction with the problem during the determination of parameter values. That is, the proposed parameter tuning method directly interacted with the problem, dynamically adjusting the parameter values to achieve better results, rather than statically enumerating possible values as was the case with the dynamic and static functions.

CONCLUSION

In this paper, the problem of informational infrastructure deployment in a static multi-cloud environment was formulated as an optimization problem, the main goal of which was to minimize the hourly cost of utilizing information infrastructure. A GA was used to solve the formulated problem. Various penalty functions were observed for the proposed algorithm, namely static, dynamic, and additive. The input parameter values were tuned for the selected penalty functions. Additionally, a S3POA parameter tuning algorithm for the penalty function parameters was proposed. The obtained results showed that the additive penalty function with parameters selected by the proposed S3POA method turned out to be better in comparison to others.

The scientific novelty. A new method was proposed that allows the decrease of information infatuation utilization cost in a static multi-cloud environment, which considers the division of the application into components and introduces restrictions on their placement. The use of different availability zones to deploy application components was also considered. Additionally, a new parameter optimization method for GA penalty functions was proposed, which allows obtaining better parameter values due to consistent interaction with the researched problem.

The practical orientation of the study. The information infrastructure deployed under the described assumptions can be used to collect data about application load and interaction patterns over a certain period. Such information provides a clear view of infrastructure needs and can be used during infrastructure operations to have reliable information on the possible service loads and resource requirements.

Prospects for further research. In future research, it makes sense to consider the usage of scalable instances. In addition, the proposed solution can be integrated into dynamic placement algorithms to be used as a starting point in the algorithm's operation.

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МЕТОД ОПТИМІЗАЦІЇ ВИТРАТ ДЛЯ РОЗМІЩЕННЯ ІНФОРМАЦІЙНОЇ ІНФРАСТРУКТУРИ В СТАТИЧНОМУ МУЛЬТИХМАРНОМУ СЕРЕДОВИЩІ

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АНОТАЦІЯ

Актуальність. Останнім часом набула популярності тема розміщення інформаційної інфраструктури в мультихмарному середовищі. Дана тенденція пов'язана з тим, що мультихмарне середовище надає можливість використовувати унікальні сервіси різних хмарних постачальників. Таким чином, всі доступні сервіси хмарних постачальників можуть бути використані при побудові інформаційної інфраструктури. Крім того, різні цінові політики серед постачальників можуть бути розглянуті при виборі сервісів. Проте зі збільшенням кількості наявних постачальників хмарних послуг зростає складність побудови оптимального плану з розміщення інформаційної інфраструктури.

Мета роботи. Метою роботи є оптимізація витрат пов'язаних з експлуатацією інформаційної інфраструктури в мультихмарному середовищі з урахуванням цін на аналогічні сервіси, серед постачальників хмарних послуг.

Метод. В роботі пропонується новий метод оптимізації витрат для розміщення інформаційної інфраструктури в статичному мультихмарному середовищі, який мінімізує погодинну вартість її використання. Для вирішення цієї задачі було використано генетичний алгоритм. Були розглянуті різні функції штрафу для генетичного алгоритму. Також пропонується новий метод підбору параметрів для функцій штрафу.

Результати. Була проведена серія експериментів для порівняння результатів різних функцій штрафу. Результати показали, що функція штрафу із запропонованим методом підбору параметрів знаходила рішення, яке було у середньому на 8,933% кращим і вимагало на 18,6% менше часу, в порівняні з іншими. Отримані результати демонструють, що запропонований метод підбору параметрів забезпечує ефективний пошук серед областей допустимих і недопустимих рішень.

Висновок. Запропоновано новий метод оптимізації витрат для розміщення інформаційної інфраструктури в статичному мультихмарному середовищі. Однак, незважаючи на ефективність запропонованого методу, його можна значно покращити. Зокрема, необхідно розглянути можливість залучення масштабованих віртуальних машин при розміщенні інформаційної інфраструктури.

КЛЮЧОВІ СЛОВА: оптимізація витрат, інформаційна інфраструктура, початкове розміщення, мультихмара, метод підбору параметрів, функція штрафів.

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IDENTIFICATION AND LOCALIZATION OF VULNERABILITIES IN SMART CONTRACTS USING ATTENTION VECTORS ANALYSIS IN A BERT-BASED MODEL

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ABSTRACT

Context. With the development of blockchain technology and the increasing use of smart contracts, which are automatically executed in blockchain networks, the significance of securing these contracts has become extremely relevant. Traditional code auditing methods often prove ineffective in identifying complex vulnerabilities, which can lead to significant financial losses. For example, the reentrancy vulnerability that led to the DAO attack in 2016 resulted in the loss of 3.6 million ethers and the split of the Ethereum blockchain network. This underscores the necessity for early detection of vulnerabilities.

Objective. The objective of this work is to develop and test an innovative approach for identifying and localizing vulnerabilities in smart contracts based on the analysis of attention vectors in a model using BERT architecture.

Method. The methodology described includes data preparation and training a transformer-based model for analyzing smart contract code. The proposed attention vector analysis method allows for the precise identification of vulnerable code segments. The use of the CodeBERT model significantly improves the accuracy of vulnerability identification compared to traditional methods. Specifically, three types of vulnerabilities are considered: reentrancy, timestamp dependence, and tx.origin vulnerability. The data is preprocessed, which includes the standardization of variables and the simplification of functions.

Results. The developed model demonstrated a high F-score of 95.51%, which significantly exceeds the results of contemporary approaches, such as the BGRU-ATT model with an F-score of 91.41%. The accuracy of the method in the task of localizing reentrancy vulnerabilities was 82%.

Conclusions. The experiments conducted confirmed the effectiveness of the proposed solution. Prospects for further research include the integration of more advanced deep learning models, such as GPT-4 or T5, to improve the accuracy and reliability of vulnerability detection, as well as expanding the dataset to cover other smart contract languages, such as Vyper or LLL, to enhance the applicability and efficiency of the model across various blockchain platforms.

Thus, the developed CodeBERT-based model demonstrates high results in detecting and localizing vulnerabilities in smart contracts, which opens new opportunities for research in the field of blockchain platform security.

KEYWORDS: smart contracts, vulnerabilities, blockchain, machine learning, attention vector analysis, transformers, code security, code audit.

ABBREVIATIONS

NN is a Neural Network;
BERT is a Bidirectional Encoder Representations from Transformers;
GPT is a Generative Pre-trained Transformer;
GRU is a Gated Recurrent Unit;
LSTM is a Long Short-Term Memory;
RNN is a Recurrent Neural Network;
CNN is a Convolutional Neural Network;
AUC is an Area Under the Curve;
ROC is a Receiver Operating Characteristic;
RGB is Red, Green, Blue;
TP is a True Positive;
FN is a False Negative;
FP is a False Positive;
TN is a True Negative.

NOMENCLATURE

C is a set of all smart contracts;
V is a set of all possible vulnerabilities;
T is a set of tokens in a smart contract code;
t_i is the i-th token in a smart contract code;
A is a set of attention weights for tokens;
a is an attention weights for the token;
$f()$ is a model that maps a smart contract to a set of vulnerabilities;
w_{ij} is an attention weight from token t_i to t_j token;
D is a dataset;
Q is a query matrix;
K is a key matrix;
V is a value matrix;
P is a value of precision;
R is a value of recall;
d_k is a key dimension;
F_β is an F score, which is a weighted harmonic mean of precision and recall;
β is a weight of recall in the F_β score;
windows_size is a size of the sliding window;
token_att_mean is a mean attention value for a token across all axes;
$windows\_sum_j$ is a sum of averaged attentions, where j is the index of the start of the window in the sequence of tokens;
start_index is a starting index from which the total windows_sum is calculated;
FPR_i is a False Positive Rate value at the i-th point;
TPR_i is a True Positive Rate value at the i-th point.

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INTRODUCTION

With the development of blockchain technology and the increasing popularity of smart contracts, the need to ensure their security has grown. Smart contracts, which are automatically executed when predetermined conditions are met, have become the foundation for numerous applications, ranging from financial transactions to voting systems. However, like any software code, smart contracts are susceptible to vulnerabilities that can lead to significant financial losses and a loss of trust in the technology. According to industry research, companies lose billions of dollars each year due to smart contract breaches, highlighting the critical need to improve methods for their protection. For example, the 2016 hack of TheDAO, in which 3.6 million Ether were stolen due to a reentrancy vulnerability, led to the split of the Ethereum blockchain and underscores the critical necessity for early detection of vulnerabilities [1].

The object of study is the security of smart contracts deployed on blockchain networks.

Detecting and eliminating vulnerabilities in smart contracts before they are deployed on the blockchain is a critically important task. Traditional code auditing methods, including manual analysis and automated static and dynamic analysis tools, often fail to fully ensure the security of smart contracts due to their limitations in identifying complex and non-obvious vulnerabilities.

The subject of study includes the methods of vulnerability detection and localization within smart contracts using machine learning techniques, with a focus on transformer-based models like BERT.

Modern methods for detecting vulnerabilities in smart contracts include symbolic execution, fuzzing, and formal verification. Well-known tools for vulnerability detection, such as Oyente, Mythril, Securify, Slither, and Smartcheck, automatically analyze contract code and can identify common types of vulnerabilities, including reentrancy issues, incorrect authorization via tx.origin, timestamp dependencies, and unhandled exceptions. However, these tools may produce false positives or miss real threats due to their reliance on predefined rules, which cannot accurately interpret complex code logic. Additionally, these preset rules quickly become outdated and cannot adapt or generalize to new data that continually evolves in the smart contract domain. Unlike these methods, deep learning approaches extract knowledge from data and can continuously update, maintaining their relevance. In recent years, researchers have been actively exploring the application of machine learning methods for software code analysis. Transformer-based models, such as BERT and its adaptations for code like CodeBERT, have shown promising results in understanding code semantics and identifying potential vulnerabilities.

The purpose of the work is to develop and validate a novel method for identifying and localizing vulnerabilities in smart contracts using attention vector analysis implemented through a CodeBERT-based model, improving the accuracy and efficiency of smart contract audits.

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1 PROBLEM STATEMENT

The task of identifying vulnerabilities in smart contracts can be formalized as follows. Let C be the set of all smart contracts, and V be the set of all possible vulnerabilities. It is necessary to build a model $f: C \to V^*$, where $f(c)$ returns the set of vulnerabilities for each contract $c \in C$.

For each contract c a set of tokens $T=\{t_1, t_2, \ldots, t_n\}$, is determined, where t_i is the i-th token of the code. The analysis of attention vectors allows determining the attention weights $A=\{a_1, a_2, \ldots, a_n\}$, where a_i is the attention weight for token t_i

For each smart contract, it is necessary to identify vulnerable code segments using attention vectors. Let w_{ij} be the attention weight from token t_i to token t_j. Then the overall attention weight for token t_i is defined as:

$$a_i = \sum_{j=1}^{n} w_{ij}.$$

2 REVIEW OF THE LITERATURE

In this section, we analyze scientific works dedicated to identifying vulnerabilities in smart contracts using deep learning technologies.

Huang et al. [2] developed a model for detecting vulnerabilities in smart contracts using convolutional neural networks. This model transforms the binary representation of vulnerable code into RGB images, complicating the preservation of syntactic and semantic information and leading to a high level of false negatives, despite improving accuracy in some cases.

Liao et al. [3] utilized N-gram modeling and tf-idf feature vectors for analyzing the source code of smart contracts. They trained traditional machine learning models to identify 13 types of vulnerabilities using real-time fuzz testing. However, designating some critical operational codes as stop-words may lead to missed vulnerabilities and false negatives.

Yu et al. [4] presented the first systematic and modular framework for detecting vulnerabilities in smart contracts based on deep learning. They introduced the concept of a “Vulnerability Candidate”, focused on analyzing dependencies between different data elements and control flow. Experiments showed a significant improvement in efficiency by 25.76% in F1 score. However, for vulnerabilities with limited data and control flow dependencies, no substantial improvement was observed.

Gao et al. [5] proposed an automated method based on word embedding representations for studying the features of smart contracts in the Solidity language. Zhang et al. [6] developed a vulnerability detection method that combines information graphs and integrated learning to extract features from smart contracts. Sendner et al. [7] were the first to propose a migration learning-based method for vulnerability detection, which uses a universal feature extractor to analyze smart contract bytecode and independent branches to analyze each type of vulnerability. Zhuang et al. [8] were the first to propose using a contract graph to represent the syntactic and semantic structures of smart contracts and applied graph convolutional neural networks for analyzing vulnerabilities based on this graph.

The analysis of existing scientific works shows that static analysis-based tools suffer from false positives and false negatives due to their reliance on predefined rules [9]. These tools are incapable of performing deep syntactic and semantic analysis, and predefined rules quickly become outdated, unable to adapt or generalize to new data. Unlike them, deep learning methods do not require predefined detection rules and can adaptively learn the characteristics of vulnerabilities during the training process.

3 MATERIALS AND METHODS

Transformers represent a neural network architecture that was first introduced in the paper "Attention is All You Need" in 2017 [10]. The main innovation of transformers is the attention mechanism, which allows models to dynamically focus on different parts of the input data, making it particularly effective for natural language processing tasks. This architecture differs from previous approaches, such as RNN and CNN, in that it is entirely based on attention without the need for sequential data processing. This significantly accelerates training and improves the handling of long dependencies in text [11].

BERT is one of the most well-known implementations of the transformer architecture, developed by Google in 2018. The main difference between BERT and preceding transformer models lies in its ability to process texts in a bidirectional manner. Traditional models, such as GPT, process text either left-to-right or right-to-left, limiting the context available to each word in a sentence. In contrast, BERT analyzes context in both directions, enabling it to better understand the contextual relationships between words. Figure 1 provides an example of the general architecture of source code classification models based on CodeBERT [12, 13].

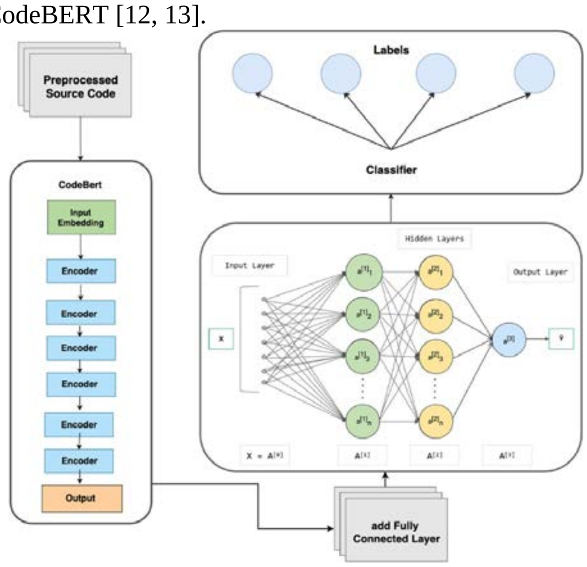

Figure 1 – General architecture of classification models based on BERT

In the context of smart contract analysis, BERT can be used for various tasks, including classification, vulnerability detection, and automatic code correction. Thanks to its ability to capture complex dependencies in the data, BERT effectively handles the syntactic and semantic features of smart contract programming languages such as Solidity [14]. This makes it an ideal tool for identifying potential vulnerabilities and errors in the code, which is critically important for ensuring the security and reliability of blockchain platforms.

An important stage of our research is data preparation, which underpins the training of a machine learning model for detecting vulnerabilities in smart contracts. To this end, we collected a dataset of 2000 Solidity smart contract source codes, each of which was analyzed using the static code analysis tool Oyente, designed to identify vulnerabilities and issues in smart contracts written in Solidity.

The dataset was divided into two categories: vulnerable and non-vulnerable smart contracts. The analysis determined that approximately 80% of the smart contracts do not contain vulnerabilities, while the remaining 20% contain one or more vulnerabilities identified using Oyente. We selected three types of vulnerabilities from the Oyente analysis results: reentrancy, timestamp dependence, and tx.origin vulnerability.

To enhance the efficiency and accuracy of model training, special attention was paid to the preprocessing of smart contract source code. In particular, the following normalization strategies were implemented:

1. Normalization of variables: All variables in the source code were renamed to a standardized format (e.g., VAR1, VAR2, ..., VARN). This reduced the diversity of the model's input data and minimized the risk of overfitting to specific or unique variable names that do not carry functional significance. This approach promotes more generalized model training, enabling it to better adapt to new, previously unseen smart contracts.

2. Simplification of functions: Auxiliary functions that do not impact the core logic of the contracts, such as logging functions or helper functions used for code simplification, were excluded. This reduces the complexity of the code input to the model and allows it to focus on functions that directly affect the contract's state and security. The remaining functions were standardized to eliminate variability in naming and approaches to performing similar operations, which also contributes to more stable and predictable model training.

To ensure effective model training, each smart contract was transformed into a format suitable for neural network processing. This included tokenizing the text of the smart contracts using the pre-trained tokenizer associated with the CodeBERT model, specifically the RobertaTokenizer from the Transformers library. However, processing long texts has always been a challenging task in the field of deep learning. Therefore, the maximum input sequence length was limited to 256 tokens, which allowed for a balance between the detail of data representation and computational resource requirements. If the extracted code contained more than 256 tokens, it was

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truncated, and code with fewer than 256 tokens was padded with zeros. This approach ensures standardized input data length, adheres to the length limits set for the CodeBERT model, and preserves the features of the vulnerabilities.

To evaluate the model's effectiveness, the dataset D was divided into three subsets: training, validation, and test:

$$D = D_{train} \cup D_{val} \cup D_{test} . \quad (1)$$

The split was performed randomly while maintaining the proportions between vulnerable and non-vulnerable smart contracts. The validation subset, comprising 20% of the total examples, was used for hyperparameter tuning and evaluating intermediate training results, while the test subset, also comprising 20% of the total examples, was used for the final assessment of the model's performance.

As the basis for vulnerability detection, we used the pre-trained CodeBERT model from Microsoft, which is an adaptation of the BERT model specifically designed for working with source code. The model was further trained on the prepared smart contract dataset to adapt it to the specifics of the task.

Smart contracts in text form are fed into the model. These texts represent the source code of smart contracts written in Solidity. The input text is transformed into a sequence of tokens using the pre-trained tokenizer associated with the CodeBERT model. The tokenizer converts the source code into a set of tokens that the model can effectively process [15]. The token sequence is fed into the BERT model (CodeBertModel). CodeBERT processes the tokens using attention mechanisms and transformers to extract contextualized vector representations of the tokens.

Instead of relying solely on the hidden state of the [CLS] token, which aggregates information across the entire sequence and is traditionally used for classification, it is proposed to use all tokens in the sequence. These tokens are fed into a single-layer Bidirectional GRU. The use of Bidirectional GRU allows the model to better capture the context in both directions (left-to-right and right-to-left), which improves the understanding of contextual relationships between tokens in a broader context [16]. This can lead to a more accurate understanding of the meaning of the entire input text and, consequently, to improved classification accuracy.

The output from the bidirectional GRU is then fed into a fully connected layer (nn.Linear), which converts the GRU output into logits for each class (in our case, binary classification into vulnerable or non-vulnerable smart contracts). The logits are converted into probabilities using the softmax function, and the class with the highest probability is chosen as the model's prediction. The model continues to minimize the CrossEntropyLoss function during training, which helps measure the difference between the model's predictions and the true class labels. The model's effectiveness is evaluated on the validation and test datasets to confirm its ability to generalize to new data [17]. Figure 2 shows the overall architecture of the proposed model.

To detect and localize vulnerabilities in smart contracts, we used attention vector analysis generated by the CodeBERT model. The attention vectors were analyzed to identify the tokens and code fragments that the model focused on most during classification. This approach allowed us not only to detect potential vulnerabilities but also to pinpoint specific locations in the code that require further analysis and corrections. This process includes several key stages:

Stage 1 involves obtaining predictions and attention vectors. The model processes the input data and returns logits for each token and attention weights. The attention weights indicate how much attention the model pays to each token while analyzing other tokens. The attention weights are calculated as follows:

$$Attention(Q,K,V) = soft\max(\frac{QK^T}{\sqrt{d_k}})V. \quad (2)$$

Stage 2 involves the selection of attention vectors from the last layer. Attention vectors from the last layer of the transformer are selected because they reflect the model's highest-level understanding of the context.

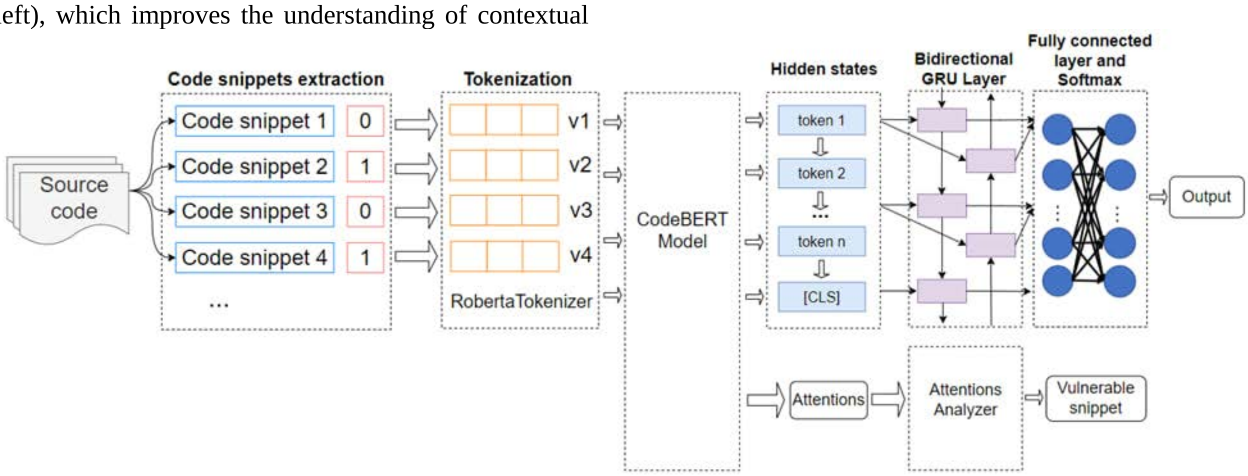

Figure 2 – General architecture of the proposed model

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Stage 3 focuses on averaging attention across heads. Attention is averaged across all heads of the attention mechanism in the last layer to obtain a generalized representation of how the model distributes its attention among tokens.

Stage 4 includes additional averaging across tokens. After averaging attention across the heads of the attention mechanism, additional averaging is performed across all tokens in the sequence. This averaging helps produce a single attention vector for the entire input set, simplifying the analysis and interpretation of which aspects of the input data the model pays the most attention to overall.

Stage 5 entails the exclusion of special tokens. The first and last tokens are excluded from the analysis because they usually contain meta-information ([CLS], [SEP]) and are not related to the substantive part of the smart contract code.

Figure 3 shows the stages of transforming the attention matrix of the last layer.

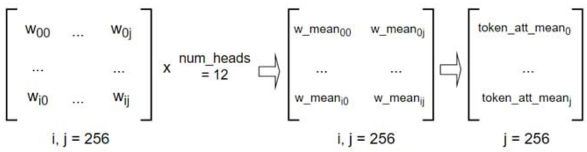

Figure 3 – Stages of transformation of the attention matrix of the last layer

Stage 6 determines important code segments. By iterating through all possible windows of a given size, the sum of averaged attention in each window is calculated. The window with the maximum sum of averaged attention is considered the most important code segment.

For each possible window of size window_size tokens, the sum of averaged attention is calculated using the following formula:

$$windows\_sum_j = \sum_{i=j}^{j+window\_size} token\_att\_mean[i]. \quad (3)$$

Next, the indices of the tokens corresponding to the window with the highest attention are determined. These tokens represent the code segment that the model considers most significant or potentially vulnerable.

The starting index of the window is calculated as follows:

$$start\_index = \arg\max_j (window\_sum_j). \quad (4)$$

Based on the starting index of the window and the window size, the tokens corresponding to the most significant code segment are selected. These tokens are then converted back to text using the tokenizer to represent the important code fragments. The result is a segment of the smart contract code that the model considers most likely to contain vulnerabilities.

This approach provides a deeper understanding of which parts of the code attract the most attention from the model, potentially indicating the presence of vulnerabilities or other critical aspects of the code.

4 EXPERIMENTS

For training the model and conducting experiments, the following software and technical resources were used. Development and testing were carried out in the Python programming language, providing flexibility and powerful capabilities for working with machine learning algorithms. The primary framework used for working with the model was Pytorch Lightning, which structured the model training process, making it cleaner, more modular, and scalable.

All development and testing were conducted on the Windows 11 operating system.

The technical configuration of the computer used for training and experiments included the following specifications:

Processor: Intel Core i9-12900K, providing high performance with its 16 cores and 24 threads, and a maximum clock speed of 5.2 GHz.

RAM: 32 GB DDR4, allowing efficient handling of large data volumes and complex models without memory constraints.

Graphics Card: NVIDIA GeForce RTX 3090 with 24 GB of GDDR6X memory.

Storage: 1 TB SSD, ensuring fast data access and efficient storage of extensive datasets and experimental results.

This configuration provided the necessary computational power and speed required for handling complex machine learning tasks and data analysis.

The model was trained using the AdamW optimizer and a learning rate scheduler, which effectively adapted the learning rate depending on the training stage. A batch size of 32 was used during training, which was conducted over 8 epochs, each consisting of 4 steps. The model included one GRU layer with a hidden state size of 16. These parameters helped avoid overfitting while achieving the best results. During training, metrics such as accuracy and loss on the training and validation sets were monitored.

Thanks to the careful tuning of parameters and the model architecture, an accuracy of 98.67% on the training data and 97.34% on the validation data was achieved (Figures 4 and 6). These results underscore the high effectiveness and adequacy of the chosen approach for solving the task.

The dynamics of the validation loss values for the training and validation data are visualized in Figures 5 and 7, respectively. These graphs illustrate how the model gradually minimized errors throughout the training process, achieving progressively lower loss values.

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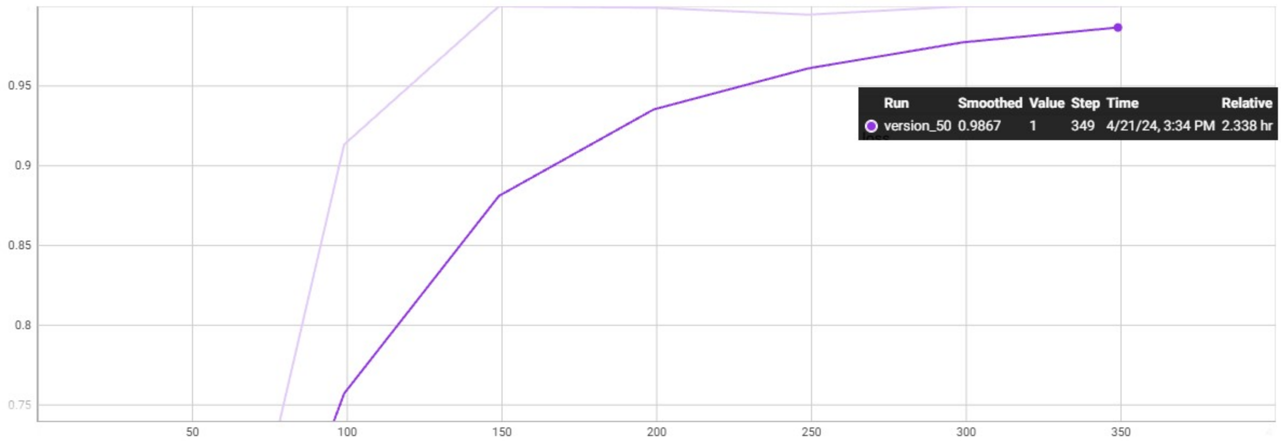

Figure 4 – Change in model accuracy during training

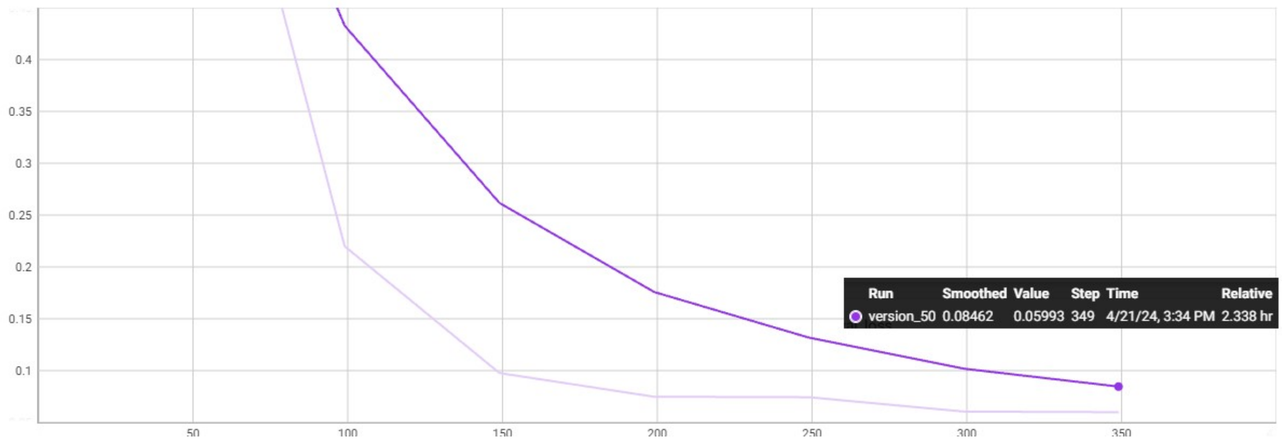

Figure 5 – Training Loss over epochs

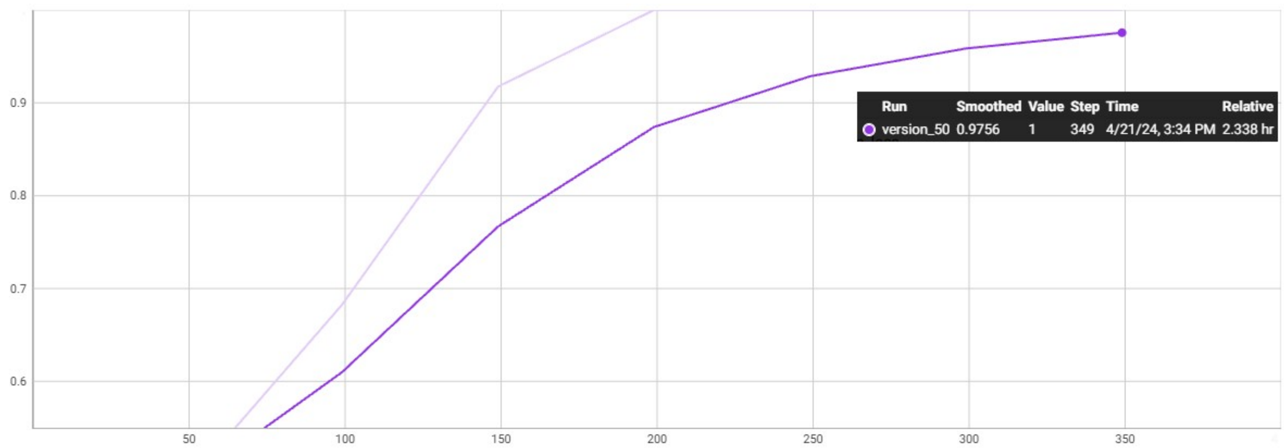

Figure 6 – Change in model accuracy during validation

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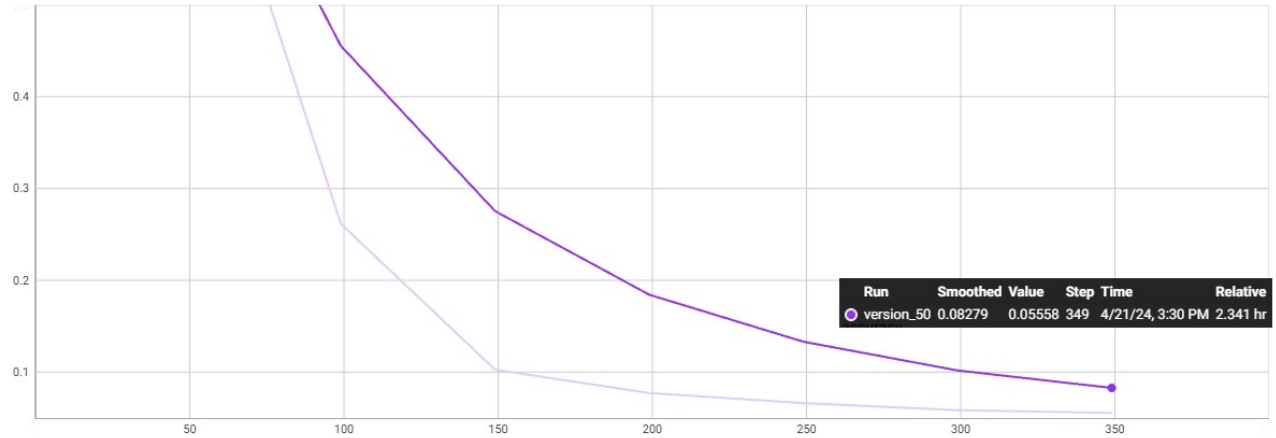

Figure 7 – Validation Loss over epochs

Figure 8 shows the confusion matrix for the test data. As can be seen from the matrix, only 7 examples were classified as False Positives and 5 as False Negatives, indicating the model's high capability to accurately identify positive cases [18]. Using the obtained confusion matrix, the model's accuracy can be calculated as follows:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} = 0.97. \qquad (5)$$

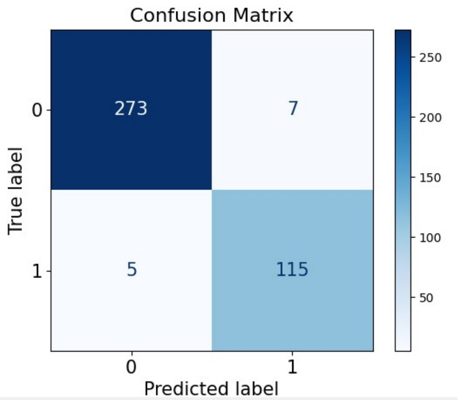

Figure 8 – Confusion matrix for test data

Furthermore, Figure 9 shows the ROC curve, with an AUC reaching 0.97, which is close to 1. This indicates that the model has excellent discriminative ability and can effectively distinguish between classes.

The area under the curve is calculated using the following formula:

$$AUC = \sum_{i=1}^{n-1}((FPR_{i+1} - FPR_i)\frac{TPR_{i+1} + TPR_i}{2}). \qquad (6)$$

Thus, the training and testing results confirm that the developed model is a reliable prediction tool capable of providing high accuracy and excellent generalization ability on new data.

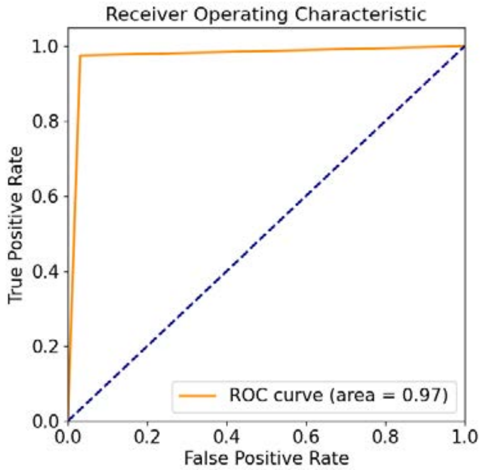

Figure 9 – ROC-curve

5 RESULTS

In our research, we analyzed various smart contracts for vulnerabilities using modern static code analysis tools. Figure 10 shows an example of Solidity code that demonstrates the classic reentrancy vulnerability.

```
contract MyContract {
    event Withdrawal(address indexed user, uint256 amount);
    event Deposit(address indexed user, uint256 amount);
    mapping(address => uint256) public balances;
    function deposit() public payable {
        balances[msg.sender] += msg.value;
        emit Deposit(msg.sender, msg.value);
    }
    function withdraw(uint256 amount) public {
        require(balances[msg.sender] >= amount, "Insufficient balance");
        (bool success, ) = msg.sender.call{value: amount}("");
        require(success, "Withdrawal failed");
        balances[msg.sender] -= amount;
        emit Withdrawal(msg.sender, amount);
    }
    function getBalance() public view returns (uint256) {
        return balances[msg.sender];
    }
}
```

Figure 10 – Example of vulnerable code

This smart contract code contains a withdraw function that may be vulnerable to reentrancy attacks due to the sequence of operations. The function first checks the balance, then makes an external call to send funds (msg.sender.call{value: amount}("")), and only after that decreases the balance. This leaves room for an attacker to repeatedly call the withdraw function during the execution of the external call, potentially allowing them to withdraw more funds than they are entitled to if the at-

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tacker controls the calling address. This violates the recommended "checks-effects-interactions pattern" design pattern, which dictates that state changes should be made before external calls [19].

To eliminate this vulnerability and enhance the security of the smart contract, it is recommended to restructure the operation logic, ensuring that all state changes are performed before calling external contracts.

During the analysis, our tool highlighted the following code segment, shown in Figure 11, as potentially vulnerable.

```
Vulnerable code snippet:

(bool success, ) = msg.sender.call{value: amount}("");
require(success, "Withdrawal failed");
balances[msg.sender] -= amount;
```

Figure 11 – Detected vulnerable code

Confirming this code segment as vulnerable not only demonstrates the risks associated with improper use of external calls in smart contracts but also validates the effectiveness of our analysis method. This highlights the importance of applying strict security patterns when developing smart contracts and the necessity of using static code analysis tools to identify and eliminate potential vulnerabilities before deploying contracts on the network.

In our research, we used heatmap visualization to analyze the attention matrices obtained from the implemented model. The heatmap provides a clear representation of which tokens in the smart contract text attract the most attention from the model.

Figure 12 shows a graph where bright vertical stripes indicate that certain tokens on the X-axis receive significant attention from many other tokens in the sequence. This suggests that such tokens may play a key role in understanding the context or contain critically important information.

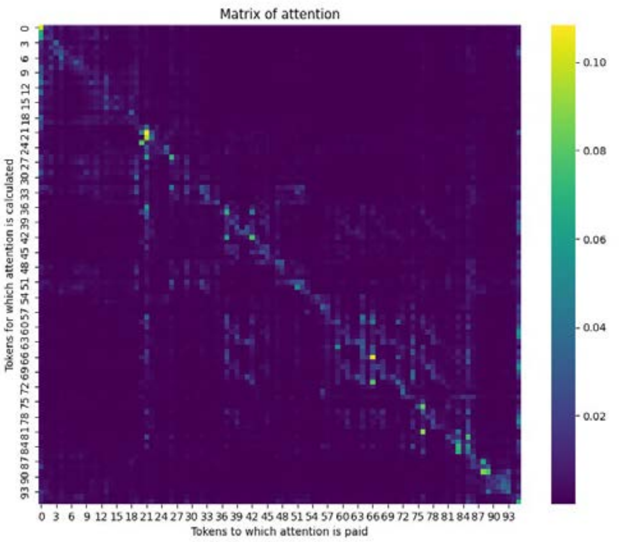

Figure 12 – Heat map of attention matrix

The model's attention to these tokens can help identify potential vulnerabilities or important aspects of the smart contract's logic, making this visualization method particularly valuable for analyzing and improving smart contract security.

In our research, we selected 50 smart contracts in which the Oyente static analysis tool identified vulnerabilities related to reentrancy issues. In each of these contracts, lines were marked where the incorrect order of method calls occurs, potentially leading to vulnerabilities. The analysis revealed that in 41 of these smart contracts, the code areas marked by the analyzer indeed contained the indicated lines, corresponding to an accuracy of 82%. This confirms the effectiveness of the applied analysis method for identifying potential vulnerabilities.

Table 1 – Experimental results

Total number of vulnerable contracts	Number of vulnerabilities correctly identified by the developed analyzer	Accuracy, %
50	41	82

In the paper [20], we evaluated various models based on key metrics. For the analysis, we selected models based on Simple RNN, LSTM, Bidirectional LSTM (BLSTM), Bidirectional GRU (BGRU), and Bidirectional LSTM with Attention Mechanism (BLSTM-ATT). The models were evaluated using the metrics precision, recall, and F-beta:

$$P = \frac{TP}{TP+FP}, R = \frac{TP}{TP+FN}, \quad (7)$$

$$F_\beta = \frac{(1+\beta^2)(P*R)}{(\beta^2*P+R)}. \quad (8)$$

The developed CodeBERT-GRU model demonstrates significantly higher results, which are presented in Table 2.

Table 2 – Comparison of the developed model with alternative models

Model	**Precision, %**	**Recall, %**	**F-score (β=2), %**
Simple RNN	66.34	64.85	65.14
LSTM	73.28	76.33	75.70
BLSTM	86.12	87.97	87.59
BGRU	86.05	88.10	87.68
BLSTM-ATT	89.87	90.66	90.50
BGRU-ATT	90.03	91.76	91.41
CodeBERT-GRU	94.26	95.83	95.51

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In the course of the study, metrics such as precision, recall, and F-measure (β=2) were used to evaluate the effectiveness of the models. Among the considered models, the developed CodeBERT-GRU model showed the best results, highlighting its high efficiency in data processing. The precision of the CodeBERT-GRU model was 94.26%, recall was 95.83%, and the F-measure reached 95.51%. These indicators are significantly higher than those of other analyzed models, such as BLSTM-ATT and BGRU-ATT, which also showed high results with F-measures of 90.50% and 91.41%, respectively. This indicates that the integration of CodeBERT with LSTM not only improves the processing of contextual information but also provides a significant improvement in recognition and classification accuracy compared to traditional models based on RNN, LSTM, and GRU.

6 DISCUSSION

The presented study offers a novel approach to identifying and localizing vulnerabilities in smart contracts through the analysis of attention vectors in a BERT-based model, specifically using CodeBERT. Our method has demonstrated a significantly higher F-score of 95.51% compared to traditional approaches like the BGRU-ATT model, which achieved an accuracy of 91.41%. Moreover, our approach for localizing reentrancy vulnerabilities has shown an accuracy of 82%, underscoring the effectiveness of the proposed method.

In comparing our results with those of other authors, it becomes evident that the application of transformer-based models, particularly CodeBERT, provides a substantial improvement in detecting and understanding code semantics.

Gao et al. [5] and Zhang et al. [6] explored automated methods based on word embeddings and integrated learning to extract features from smart contracts. Sendner et al. [7] and Zhuang et al. [8] proposed using migration learning and graph convolutional neural networks for vulnerability analysis, respectively. While these methods have shown promise, our approach's integration of CodeBERT with bidirectional GRU layers enhances the model's ability to contextualize and understand code, leading to superior performance metrics.

A major issue with previous machine learning-based methods, including those described in ESCORT [21], was their inability to precisely pinpoint the vulnerable code segments; they could only indicate whether the code was vulnerable or not. ESCORT, for instance, leverages a multi-output neural network architecture with a common feature extractor and multiple branch structures, achieving an average F1-score of 95% on six vulnerability types and 93% when extended to new types. However, it still primarily focuses on whether a contract is vulnerable and lacks the precise localization of vulnerabilities within the code. Our method addresses this limitation by enabling precise localization of the vulnerable code segments, providing more detailed and actionable insights for developers.

Our model's performance metrics, with a precision of 94.26% and a recall of 95.83%, indicate a well-balanced approach to vulnerability detection. The high precision value signifies that the model is highly effective in minimizing false positives, ensuring that the identified vulnerabilities are indeed present in the smart contracts. This reduces the likelihood of unnecessary alarm and enables developers to focus on actual issues. Meanwhile, the high recall value demonstrates the model's capability to identify the majority of actual vulnerabilities, minimizing false negatives and ensuring that most vulnerabilities are detected. This balance between precision and recall reflects the robustness of our model in maintaining high accuracy while effectively reducing both false positives and false negatives.

The limitations of our study include the focus on Solidity smart contracts and the reliance on static code analysis. Expanding the dataset to include other smart contract languages such as Vyper and LLL could enhance the generalizability of our model. Furthermore, incorporating dynamic analysis techniques alongside static analysis could provide a more comprehensive understanding of the contract's behavior, thus increasing the detection rate of complex vulnerabilities that manifest only during execution.

Practically, the results of our research can be applied to improve the security auditing processes for smart contracts. By integrating our model into existing auditing tools, developers can identify and address vulnerabilities more effectively before deployment, reducing the risk of financial losses and enhancing trust in blockchain technologies.

Future research directions include the integration of more advanced deep learning models such as GPT-4 or T5, which could further improve the accuracy and robustness of vulnerability detection. Additionally, expanding the dataset to cover a wider variety of smart contract languages and incorporating dynamic analysis techniques could provide a more holistic approach to smart contract security.

In conclusion, our study demonstrates that the application of transformer-based models like CodeBERT significantly enhances the detection and localization of vulnerabilities in smart contracts. This approach offers a promising direction for future research and practical applications in the field of blockchain security.

CONCLUSIONS

In our study, we presented an innovative approach to identifying and localizing vulnerabilities in smart contracts using attention vector analysis in the CodeBERT model. This method not only effectively determines the presence of vulnerabilities but also precisely points to the areas in the code that require developers' attention. This has been made possible by the deep understanding of the context and semantics of the code, which is a significant advantage over traditional auditing methods.

We successfully achieved an accuracy of 97.34% with the developed CodeBERT model, which is significantly

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higher compared to the accuracy of the BGRU-ATT model, which was 90.03%. Furthermore, the vulnerability localization method demonstrated an accuracy of 82% in identifying reentrancy vulnerabilities, confirming the effectiveness of this approach for detecting specific types of vulnerabilities in smart contracts.

The confirmation of the effectiveness of our approach is reflected in the significant improvement in vulnerability detection results compared to existing methods, as highlighted in our experimental results. The use of the CodeBERT model for analyzing smart contracts has opened new opportunities for research in the field of blockchain security.

Finally, the results of our study can serve as a foundation for further development of machine learning methods in the field of blockchain platform cybersecurity. They also emphasize the importance of continuing research in this area, aimed at improving auditing technologies and smart contract development to ensure their reliability and security.

The scientific novelty of our research is rooted in the development and validation of a novel approach for identifying and localizing vulnerabilities in smart contracts using attention vector analysis within a BERT-based model. Unlike traditional methods, our approach leverages the deep contextual understanding provided by CodeBERT, significantly enhancing the model's accuracy and robustness. A major issue with previous machine learning-based methods was their inability to precisely pinpoint the vulnerable code segments; they could only indicate whether the code was vulnerable or not. Our innovative method addresses this limitation by enabling precise localization of the vulnerable code segments, offering more detailed and actionable insights for developers. This advancement marks a significant step forward in the application of transformer-based models to the field of blockchain security.

The practical significance of our research lies in its potential to enhance security auditing processes for smart contracts. By integrating our model into existing auditing tools, developers can more effectively identify and address vulnerabilities before deployment, thereby reducing the risk of financial losses and enhancing trust in blockchain technologies.

Prospects for further research include several promising directions based on the results obtained in this study. First, the integration of more advanced deep learning models, such as transformers with enhanced attention mechanisms like GPT-4 or T5, could further improve the accuracy and robustness of vulnerability detection and localization in smart contracts. Second, expanding the dataset to include a wider variety of smart contract languages beyond Solidity, such as Vyper or LLL, could generalize the model's applicability and effectiveness across different blockchain platforms. Additionally, incorporating dynamic analysis techniques alongside the static analysis employed in this study could provide a more comprehensive understanding of the contract's behavior, thereby increasing the detection rate of complex vulnerabilities that manifest only during execution. These future directions hold the potential to greatly advance the field of smart contract security and contribute to the broader adoption and trust in blockchain technologies.

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ІДЕНТИФІКАЦІЯ ТА ЛОКАЛІЗАЦІЯ ВРАЗЛИВОСТЕЙ У СМАРТ-КОНТРАКТАХ З ВИКОРИСТАННЯМ АНАЛІЗУ ВЕКТОРІВ УВАГИ В МОДЕЛІ НА ОСНОВІ BERT

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АНОТАЦІЯ

Актуальність. З розвитком технології блокчейн та зростанням використання смарт-контрактів, які автоматично виконуються в блокчейн-мережах, значущість безпеки цих контрактів стала надзвичайно актуальною. Традиційні методи аудиту коду часто виявляються неефективними для виявлення складних уразливостей, що може призвести до значних фінансових втрат. Наприклад, уразливість повторного входу, яка призвела до атаки на DAO в 2016 році, спричинила втрату 3,6 мільйона ефірів та поділ блокчейн-мережі Ethereum. Це підкреслює необхідність раннього виявлення уразливостей.

Мета роботи – розробка та апробація новаторського підходу до виявлення та локалізації уразливостей у смарт-контрактах на основі аналізу векторів уваги в моделі, що використовує архітектуру BERT.

Метод. Описується методика, яка включає підготовку даних та навчання трансформерної моделі для аналізу коду смарт-контрактів. Запропонований метод аналізу векторів уваги дозволяє точно ідентифікувати уразливі ділянки коду. Використання моделі CodeBERT значно покращує точність ідентифікації уразливостей порівняно з традиційними методами. Зокрема, розглядаються три типи уразливостей: повторний вхід, залежність від часу та уразливість tx.origin. Дані попередньо нормалізуються, що включає стандартизацію змінних та спрощення функцій.

Результати. Розроблена модель продемонструвала високий F-score на рівні 95,51%, що значно перевищує результати сучасних підходів, таких як модель BGRU-ATT з F-score 91,41%. Точність методу у завданні локалізації уразливості повторного входу склала 82%.

Висновки. Проведені експерименти підтвердили ефективність запропонованого рішення. Перспективи подальших досліджень включають інтеграцію більш просунутих моделей глибокого навчання, таких як GPT-4 або T5, для покращення точності та надійності виявлення уразливостей, а також розширення набору даних для охоплення інших мов смарт-контрактів, таких як Vyper або LLL, для підвищення застосовності та ефективності моделі на різних блокчейн-платформах.

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Таким чином, розроблена модель на основі CodeBERT демонструє високі результати у виявленні та локалізації вразливостей у смарт-контрактах, що відкриває нові можливості для досліджень у сфері безпеки блокчейн-платформ.

КЛЮЧОВІ СЛОВА: смарт-контракти, вразливості, блокчейн, машинне навчання, аналіз векторів уваги, трансформери, безпека коду, аудит коду.

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УПРАВЛІННЯ У ТЕХНІЧНИХ СИСТЕМАХ

CONTROL IN TECHNICAL SYSTEMS

UDC 629.764

MARGIN OF STABILITY OF THE TIME-VARYING CONTROL SYSTEM FOR ROTATIONAL MOTION OF THE ROCKET

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ABSTRACT

Context. The rocket motion control system is time-varying, since its parameters during flight depend on the point of the trajectory and fuel consumption. Stability margin indicators are determined in a limited area of individual points of the trajectory using algorithms that are developed only for linear stationary systems, which leads to the need to enter stock factor in hardware. In the available sources, due attention is not paid to the development of methods for determining the quantitative assessment of the stability margin of the time-varying control system.

Objective is to develop a methodological support for the construction of an algorithm for calculating the stability margin indicators of the time-varying system for controlling the rocket rotational motion in the plane of yawing using the equivalent stationary approximation at a selected trajectory section**.**

Method. The mathematical model of the control system for the rocket rotational movement in one plane is adopted in the form of a linear differential equation without considering the inertia of the executive device and other disturbing factors. The effect of deviation of parameters from their average values for a certain trajectory section is considered as a disturbance, which makes it possible to transition from a non-stationary model to an equivalent approximate stationary one. The Nyquist criterion is used to estimate the stability margin indicators, which is based on the analysis of the frequency characteristic of an open system, for the determination of which the Laplace transform mathematical apparatus is used. To simplify the transition from functions of time in the differential equation of perturbed motion to functions of a complex variable in the Laplace transform, time-varying model parameters are presented in the form of a sum of exponential functions.

Result. Methodological support was developed for building an algorithm for determining the stability margin of the rocket's rotary motion control system at a given trajectory section with time-inconstant parameters.

Conclusions. Using the example of the time-varying system for controlling the rocket rotational movement, the possibility of using the Laplace transformation to determine the stability margin indicators is shown.

The obtained results can be used at the initial stage of project work.

The next stage of the research is an assessment of the level of algorithm complexity, considering the inertia of the executive device and the disturbed movement of the mass center.

KEYWORDS: rocket motion control, time-varying system, Laplace transform.

ABBREVIATIONS

APFC is an amplitude-phase frequency characteristic;

LC is law of control;

LTV is a linear time-varying system;

MLS is the method of least squares;

CO is the control object;

TF is a transfer function;

CS is the control system for rotational motion of the rocket in the yaw plane;

LF is a Lyapunov function;

CP is a characteristic polynomial.

NOMENCLATURE

$\bar{a}_{\psi\psi}, \bar{a}_{\psi\delta}$ are average values of parameters of the CS model at the trajectory section;

$\tilde{a}_{\psi\psi}(t), \tilde{a}_{\psi\delta}(t)$ are variable components of the model parameters at the trajectory section depending on the time from the beginning of the section;

$C_{\psi i}, C_{\delta i}$ are coefficients in the i-th term of the approximation of variable component of the model parameters by the sum of exponential functions;

$d \cdot 1(t)$ is a signal at the input of the CS;

f_1 is a specified value of the frequency of the missile body oscillations in the transient process of disturbance compensation;

f_{2k} , f_2 are frequency of the rocket body oscillations in the transient process of disturbance compensation at the k-th step of the iterations and one after their end;

j is an imaginary unit;

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k is a current number of iteration;

k_ψ, k'_ψ are coefficients of LC;

l is the number of rows in the array N;

$L\{f(t)\}$ is the Laplace transform operator of the time function;

m is a disruptive acceleration;

N is a array of polynomial $Q_k(s)$ depending on the l argument values;

$P(s), Q(s)$ are numerator and denominator of the TF $w_z(s)$;

$Q_a(s)$ is a denominator of the TF $w(s)$;

Q_0 is a first approximation of the denominator of the TF $w_z(s)$;

$Q_k(s)$ is a denominator of TF $w_z(s)$ at the k-th iterations step;

$Qd(s,\psi_{cur})$ is a component CP of CS caused by the instability of the model parameters depending on the complex variable s and the image ψ_{cur} of the signal at the output of the CS;

q_{2k}, q_{1k}, q_{0k}, q_2, q_1, q_0 are coefficients of CP $Q(s)$ at the k-th iterations step and after their completion;

$r_{\psi i}$, $r_{\delta i}$ are exponents of the exponential functions in the i-th term of approximation of variable components of the model parameters $\tilde{a}_{\psi\psi}(t), \tilde{a}_{\psi\delta}(t)$;

s_i is an i-th value of complex argument s;

$u(\omega), v(\omega)$ are real and imaginary component of the APFC of the open CS;

$u\ jv$ is a plane of the real and imaginary components of the APFC $w(s)$ of the opened CS;

$w(s)$ is a TF of the opened CS;

$w_z(s), w_m(s)$ are TF of CS;

$w_{z0}(s)$ is a first approximation of TF $w_z(s)$;

$w_{zk}(s)$ is a TF $w_z(s)$ at the k-th step of the iterations;

δ is an equivalent rotation angle of the steering wheel of the CS regulator's executive device;

η_1 is a specified value of the stability margin on the CP roots plane;

η_{2k}, η_2 are margins of stability on the CP roots plane at the k-th iteration step and after its end;

η_a, η_{ph} are CS stability margin indicators by amplitude and by phase;

η_{act}, η_{phct} are stability margin indicators when using the method of frozen coefficients;

$\psi, \dot{\psi}, \ddot{\psi}$ are yaw angle and its derivatives;

$\psi_g, \dot{\psi}_g$ are given values of the yaw angle and its derivative;

$\psi_0(s)$ is a first approximation of the image of the output signal of the CS;

ω_1 is a value of the circular frequency at which the APFC of the open CS crosses a circle of unit radius.

INTRODUCTION

The main requirements for the CS, as that's known are to ensure the specified parameters of the stability margin indicators and the accuracy of the trajectory. The fulfillment of these requirements is achieved by choosing the structure and parameters of the regulator and modeling the disturbed motion of the rocket in the vicinity of the nominal kinematic values.

At the first stage of CS development, a mathematical apparatus is used in the form of a system of linear differential equations with parameters that are assumed to be constant in the vicinity of a certain trajectory point [1], while as a result of fuel consumption, an increase in speed and flight altitude, the parameter values can change by tens of percent. That is, the so-called method of frozen coefficients is used, as a result, the dependence of the parameter on time is a piecewise-constant function. The advantage of this approach is the possibility of using it to solve the problems of analysis and synthesis of the mathematical apparatus of linear stationary systems, in particular, the Laplace transformation and obtaining the TF, based on which the accuracy and stability indicators are determined. The disadvantage is the presence of an error in the value of the model parameters, which is the largest at the extreme points of the selected time interval. This leads to the need to introduce reserve factors to obtain the specified values of the indicators guaranteed, which leads to an increase in the requirements for the power of the CS executive device and, as a result, to a decrease in the weight of the rocket's payload.

In this work, on the interval of the trajectory, where the time-varying system is matched by an equivalent stationary one, the variable component of the model parameter is approximated by exponential smoothing, which, thanks to the known properties of the Laplace transform, significantly simplifies the algorithm for obtaining the TF in comparison with approximation by other functions, for example, power series.

The TF includes a component that describes the influence of time instability of the model parameters on the CS indicators, but its coefficients on the selected trajectory interval do not depend on time, that is, it is a mathematical model of an equivalent stationary system.

Compared to the method of frozen coefficients, where the dependence of the parameter on time is a piecewise constant function and the largest error take place at the extreme points of the interval, the error of the parameter is determined only by the accuracy of exponential smoothing.

The TF of an equivalent stationary system makes it possible to determine the dependence of the CS indicators, particularly the margin of stability on the design parameters by using the mathematical apparatus of stationary systems.

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The object of the study is the control of the rotational movement of the rocket in the yaw plane.

The subject of the study is the stationary approximation of the LTV at a given time interval obtained by using the Laplace transform of non-time-constant components of the CS model.

The purpose of the work is to develop a methodical support for the construction of an algorithm for calculating the indicators of the margin of stability of the time-varying system of controlling the rotational motion of the rocket in the plane of yawing using the equivalent stationary approximation on a given time interval.

1 PROBLEM STATEMENT

The known in the theory of automatic control approach to determine the margin of stability uses the APFC of an open control system and based on the Nyquist criterion, according to which is performed an analysis of its location relative to the critical point with coordinates –1, j0 on the plane of real and imaginary parts of the APFC.

CS open at point A is a series connection of the regulator and CO (Fig. 1). The rotary motion of the rocket in the plane of yawing is taken as the CO, the input signal of which is perturbing acceleration *m* and the equivalent rotation angle δ of the regulator's executive device.

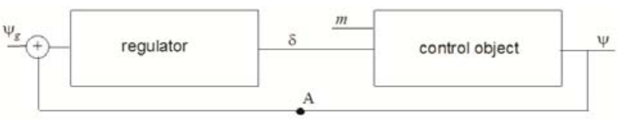

Figure 1 – Control sysems structural schema

The level of complexity of CS mathematical models depends on the research task. The order of the system of differential equations can be between 2 and 16.

For example, the disturbed motion of a typical three-stage space rocket in the channel of yawing, considering the first harmonic of fuel vibrations in four tanks and two-tone elastic oscillations of the rocket body, is described by a system of differential equations of the 16-th order [1].

The study of the stability of the rotational movement of the rocket at the first stage of design can be carried out without considering the fluctuations of the fuel in the tanks, the inertia of the executive device, the disturbed movement of the mass center and the final stiffness of the rocket body, since the frequency spectrum of the mentioned factors overlaps insignificantly. As a result the CO is considered as a rigid body, and the disturbed motion in one of the stabilization planes (for example, in the plane of yawing) is described by a second-order differential equation, the coefficients of which have the constant and time-variable components:

$$\ddot{\psi} = a_{\psi\psi}(t)\cdot\psi + a_{\psi\delta}(t)\cdot\delta + m =$$
$$= [\bar{a}_{\psi\psi} + \tilde{a}_{\psi\psi}(t)]\cdot\psi + [\bar{a}_{\psi\delta} + \tilde{a}_{\psi\delta}(t)]\cdot\delta + m \,. \qquad (1)$$

In this work, on the example of the rotational motion of a "solid" rocket in one plane, the possibility of obtaining a stationary approximation of the LTV on a selected trajectory section by applying the Laplace transformation of equation (1) is considered, where the variable components of the model parameters $a_{\psi\psi}(t)$ and $a_{\psi\delta}(t)$ are given by the sum of exponential functions.

As a result, the TF of the open system and, accordingly, the APFC, based on which the indicators of the margin of stability are determined, do not depend on time, as in stationary systems.

This approach complements the methodical base of design work, as it makes it possible to establish trajectory intervals with constant LC coefficients, which has the consequence of reducing the level of complexity of the rocket motion control algorithm.

2 REVIEW OF THE LITERATURE

The issue of analysis and synthesis of LTV is an integral part of the theory of automatic control, the development of which is caused by the need to solve several technical problems, particularly, the design of CS for the movement of aircraft. For their research, with the aim of determining the LC that provides the specified indicators, various variants of the mathematical apparatus is used, for example, Lyapunov differential inequalities, matrix polynomials, Lyapunov – Krasovsky functionals, Lyapunov – Bregman functions, Lyapunov's parametric equations, models predictive control, differential equations with constant coefficients around a certain time.

Analysis of stability of LTV compared to stationary systems is much more complicated for several reasons. First, another formulation of the concept of stability, secondly, there is no obvious connection between the stability of the LTV and the eigenvalues of the matrix of the equations system. In addition, the result of the analysis largely depends on the state transition matrices, the possibility of determining which is obvious not always [2].

The construction of LF for LTV is related to the solution of a scalar differential equation, which contains both improper and double integrals [3]. For scalar LTV, a method of LF construction based on the use of the integral of the system parameter with a weight function on a finite interval is proposed. Conditions are imposed on the weight function so that LF is positively defined and uniformly bounded, and its time derivative according to the LTV equations is negatively defined, which is a criterion of stability.

New methods of LF construction for a certain class of LTV are proposed [4], Lyapunov's inverse theorem for asymptotic stability is proved. Its necessary and sufficient conditions are obtained based on the proved Lyapunov's differential inequalities [5].

With the use of Riccati equations and matrix inequalities, an algorithm for assessing the stability of LTV, whose disturbances are described by quadratic constraints, was developed [6].

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Obtaining the specified technical indicators of the LTV by using the Lyapunov stability theory is shown on the examples of spacecraft orientation systems [7, 8]; control of the disturbed movement of the aircraft in the pitch plane [9], the movement of the aircraft with vertical take-off and landing [10, 11], the glider in the presence of prohibited flight zones [12–14], guidance when meeting the conditions at the end of the flight interval [15].

The effectiveness of using Lyapunov's differential inequalities for the construction of the algorithm for the calculation of CL is shown, which provides a compromise between the requirements of speed and accuracy of stabilization, the properties of the transient process are established, and the assumption of a limited range of coefficient changes is removed.

The concept of building a dynamic controller in LTV feedback, when its parameters are known only approximately, has been developed [16]. The sufficient and necessary conditions for the possibility of solving the problem in the form of matrix inequalities are obtained, based on which the parameters of the controller are determined.

In the control system of the rocket rotational movement the model parameters deviation from the time-varying nominal values can amount to ten or more percent, therefore, to increase the efficiency of using the method of frozen coefficients, an algorithm for their refinement by using the data of measuring devices on the current values of part of the state vector coordinates is proposed [17]. Algorithms for specifying LTV parameters for various types of disturbances are also described in works [18–21].

The presence of non-linear links in the aircraft traffic CS complicates the task of obtaining the specified indicators, particularly, the stability margin. Linearization of non-linear links at certain points of the trajectory leads to LTV. The perespective method of predictive control [22, 23] was used for their research. An example of its application can be a predictive controller for solving the problem of meeting spaceships in the context of a limited three-body problem, which can be used to control the docking process with space stations between the Earth and the Moon [24].

The analysis of available sources shows that the problem of quantitative assessment of the stability margin of time-varying control systems, in particular systems for controlling the rocket rotational movement does not have a proper solution.

Based on the equivalent stationary approximation of the LTV on a certain trajectory section, this indicator can be defined as the reduced smallest distance from the selected point in the space of LC coefficients to the boundary of the stability region or on the plane of the CP roots as the distance from its imaginary axis to the nearest root, and also based on the criterion stability by Nyquist through analyzing the APFC of an open system as a amplitude margin and phase margin.

3 MATERIALS AND METHODS

As is known, the sequence of determining the CS stability margin includes the following actions: the choice of a mathematical model, for example, in the form of differential equations; their Laplace transformation and obtaining the TF; transition from TF to APFC of an open system under the condition of using the Nyquist stability criterion.

Representation of the variable component of parameters of the CS model (Fig. 1) by the sum of exponential functions has advantages from the point of view of the level of complexity of the transition from differential equations (1) to TF. This follows from the well-known properties of the Laplace transform of the time function $f(t)$ into a function of the complex variable *s*, which is called the image and can be written as:

$$L\{f(t)\} = \int_0^{\infty} f(t) \cdot e^{-s \cdot t} \cdot dt . \qquad (2)$$

When the approximation of the variable component of the CS model parameter is carried out by the sum of, for example, six exponential functions, that is

$$\tilde{a}_{\psi\psi}(t) = \sum_{i=1}^{6} C_{\psi i} \cdot e^{r_{\psi i} \cdot t} , \qquad (3)$$

then based on (2, 3) the Laplace transform of the separate component of equation (1) according to the image delay theorem will be as follows

$$L\{\psi \cdot \tilde{a}_{\psi\psi}(t)\} = L\{\psi \cdot \sum_{i=1}^{6} C_{\psi i} \cdot e^{r_{\psi i} \cdot t}\} = \sum_{i=1}^{6} C_{\psi i} \cdot \psi(s - r_{\psi i}) . \qquad (4)$$

Therefore, relation (4) gives the Laplace transformation of the product of the yaw angle ψ on the variable component of the model parameter, which has the consequence of simplifying the transition from the CS differential equation to the TF.

If in LC – the dependence of the equivalent rotation angle δ of the regulator's executive device steering wheel on the given and actual value of the yaw angle ψ_g, ψ are taken into account with the coefficients k_{ψ}, k'_{ψ} their time derivatives $\dot{\psi}_g, \dot{\psi}$, that is

$$\delta = (\psi_g + \psi) \cdot k_{\psi} + (\dot{\psi}_g + \dot{\psi}) \cdot k'_{\psi} , \qquad (5)$$

then in the CS model (1) there will also be products of the yaw angle ψ and its derivative $\dot{\psi}$ on the variable component of the model parameter $a_{\psi\delta}(t)$:

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$$\psi \cdot \tilde{a}_{\psi\delta}(t) = \psi \cdot \sum_{i=1}^{6} C_{\delta i} \cdot e^{r_{\delta i} \cdot t},$$

$$\dot{\psi} \cdot \tilde{a}_{\psi\delta}(t) = \dot{\psi} \cdot \sum_{i=1}^{6} C_{\delta i} \cdot e^{r_{\delta i} \cdot t}. \qquad (6)$$

The use of ratios (2, 4, 6) and the method of integration by parts establishes a connection between the individual terms of the CS equation (1) and their images:

$$L\{\psi \cdot \tilde{a}_{\psi\delta}(t)\} = \sum_{i=1}^{6} C_{\delta i} \cdot \psi(s - r_{\delta i}),$$

$$L\{\dot{\psi} \cdot \tilde{a}_{\psi\delta}(t)\} = \sum_{i=1}^{6} C_{\delta i} \cdot \psi(s - r_{\delta i}) \cdot (s - r_{\delta i}). \qquad (7)$$

According to (1, 3–7), the CS equation can be written in the form:

$$\ddot{\psi} - \psi \cdot (\bar{a}_{\psi\psi} + \sum_{i=1}^{6} C_{\psi i} \cdot e^{r_{\psi i} \cdot t}) -$$
$$-(k_\psi \cdot \psi + k_\psi' \cdot \dot{\psi}) \cdot (\bar{a}_{\psi\delta} + \sum_{i=1}^{6} C_{\delta i} \cdot e^{r_{\delta i} \cdot t}) =$$
$$= (k_\psi \cdot \psi_g + k_\psi' \cdot \dot{\psi}_g) \cdot (\bar{a}_{\psi\delta} + \sum_{i=1}^{6} C_{\delta i} \cdot e^{r_{\delta i} \cdot t}) + m. \qquad (8)$$

It's known the principle of superposition is valid for linear systems, according to which the result of the action of the input signal $\psi_g(t)$ or $m(t)$ can be determined independently. In order to build an algorithm for calculating indicators of the CS stability margin from two possible TFs

$$w_z(s) = \frac{L\{\psi(t)\}}{L\{\psi_g(t)\}} = \frac{\psi(s)}{\psi_g(s)},\ w_m(s) = \frac{L\{\psi(t)\}}{L\{m(t)\}} = \frac{\psi(s)}{m(s)}, \quad (9)$$

in this work, the TF $w_z(s)$ is selected, which is determined by the Laplace transformation of equation (8) at zero initial values.

To obtain the TF, the differential equation (8) is transformed into an algebraic one with respect to the images of the actual $\psi(s)$ and specified $\psi_g(s)$ value of the yaw angle:

$$\psi(s) \cdot [s^2 - k_\psi' \cdot \bar{a}_{\psi\delta} \cdot s - k_\psi \cdot \bar{a}_{\psi\delta} - \bar{a}_{\psi\psi} -$$
$$-\sum_{i=1}^{6} C_{\psi i} \cdot \frac{\psi(s - r_{\psi i})}{\psi(s)} - k_\psi \cdot \sum_{i=1}^{6} C_{\delta i} \cdot \frac{\psi(s - r_{\delta i})}{\psi(s)} -$$
$$-k_\psi' \cdot \sum_{i=1}^{6} C_{\delta i} \cdot \frac{\psi(s - r_{\delta i}) \cdot (s - r_{\delta i})}{\psi(s)}] =$$
$$= \psi_g(s) \cdot [\bar{a}_{\psi\delta} \cdot (k_\psi + k_\psi' \cdot s) +$$
$$+ k_\psi \cdot \sum_{i=1}^{6} C_{\delta i} \cdot \frac{\psi_g(s - r_{\delta i})}{\psi_g(s)} +$$
$$+ k_\psi' \cdot \sum_{i=1}^{6} C_{\delta i} \cdot \frac{\psi_g(s - r_{\delta i}) \cdot (s - r_{\delta i})}{\psi_g(s)}]. \qquad (10)$$

Equation (10) makes it possible to obtain the TF $w_z(s)$ in the form of a fractional-rational function of a complex-type argument *s*:

$$w_z(s) = \frac{\psi(s)}{\psi_g(s)} = \frac{P(s)}{Q(s)},$$

where the designations are accepted:

$$P(s) = \bar{a}_{\psi\delta} \cdot (k_\psi + k_\psi' \cdot s) + k_\psi \cdot \sum_{i=1}^{6} C_{\delta i} \cdot \frac{\psi_g(s - r_{\delta i})}{\psi_g(s)} +$$
$$+ k_\psi' \cdot \sum_{i=1}^{6} C_{\delta i} \cdot \frac{\psi_g(s - r_{\delta i}) \cdot (s - r_{\delta i})}{\psi_g(s)}, \qquad (11)$$

$$Q(s) = s^2 - k_\psi' \cdot \bar{a}_{\psi\delta} \cdot s - k_\psi \cdot \bar{a}_{\psi\delta} - \bar{a}_{\psi\psi} -$$
$$-\sum_{i=1}^{6} C_{\psi i} \cdot \frac{\psi(s - r_{\psi i})}{\psi(s)} - k_\psi \cdot \sum_{i=1}^{6} C_{\delta i} \cdot \frac{\psi(s - r_{\delta i})}{\psi(s)} -$$
$$-k_\psi' \cdot \sum_{i=1}^{6} C_{\delta i} \cdot \frac{\psi(s - r_{\delta i}) \cdot (s - r_{\delta i})}{\psi(s)}. \qquad (12)$$

Iterations are necessary to obtain the TF $w_z(s)$, since the image of the output signal $\psi(s)$ is included in the last three terms of the equation (10) left part, which are a consequence of the time instability of the model parameters on the trajectory's selected section and considered as a disturbance in this work.

To obtain the first approximation of the image of the output signal $\psi_0(s)$ necessary for the iterations, the image of the signal at the input of the CS $\psi_g(s)$ is required, the choice of which does not affect the indicators of the stability margin. From the point of view of the complexity level of the algorithm, it can be taken as constant – single signal with accuracy up to the factor *d*, that is $\psi_g(t) = d \cdot 1(t)$. Then according to (2) $\psi_g(s) = d / s$.

When the disturbance is not taken into account, then in equation (10) terms with coefficients $C_{\psi i}, C_{\delta i}$ are assumed to be zero and the first approximation of the TF $w_z(s)$ will have the form

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$$w_{z0}(s)=\frac{\psi_0(s)}{\psi_g(s)}=\frac{\bar{a}_{\psi\delta}\cdot(k_\psi+k_\psi^{'}\cdot s)}{s^2-\bar{a}_{\psi\delta}\cdot k_\psi^{'}\cdot s-k_\psi\cdot\bar{a}_{\psi\delta}-\bar{a}_{\psi\psi}}. \quad (13)$$

The first approximation of the output signal's image

$$\psi_0(s)=\psi_g(s)\cdot w_{z0}(s)=d\cdot w_{z0}(s)/s.$$

Numerator (11) of TF $w_z(s)$

$$P(s)=\bar{a}_{\psi\delta}\cdot(k_\psi+k_\psi^{'}\cdot s)+$$
$$+s\cdot(k_\psi\cdot\sum_{i=1}^{6}\frac{C_{\delta i}\cdot}{s-r_{\delta i}}+k_\psi^{'}\cdot\sum_{i=1}^{6}C_{\delta i}) \quad (14)$$

according to equation (10) and relations for the terms of its right-hand side:

$$\frac{\psi_g(s-\alpha)}{\psi_g(s)}=\frac{s}{s-\alpha},\quad \frac{\psi_g(s-\alpha)\cdot(s-\alpha)}{\psi_g(s)}=s.$$

The LC coefficients (5) k_ψ and $k_\psi^{'}$, which are included in (8, 10–14), are determined for the selected trajectory interval based on the given previous values of the margin of stability η_1 on the CP roots plane and the frequency f_1 of the rocket body oscillations in the transient process of disturbance compensation:

$$k_\psi=-(\eta_1^2+4\pi^2\cdot f_1^2+\bar{a}_{\psi\psi})/\bar{a}_{\psi\delta},\quad k_\psi^{'}=-2\eta_1/\bar{a}_{\psi\delta}. \quad (15)$$

Relations (15) are obtained from the fact that the roots of the denominator Q_0 of the first TF approximation (13) according to the values η_1 and f_1 are as follows:

$$s_{1,2}=-\eta_1\pm j\cdot 2\pi\cdot f_1.$$

Iterations to determine the denominator $Q(s)$ TF $w_z(s)$ – CP can be carried out according to the scheme:

$$Q_k(s)=Q_0(s)-\frac{1}{\psi_{k-1}(s)}\cdot\left[\sum_{i=1}^{6}C_{\psi i}\cdot\psi_{k-1}(s-r_{\psi i})-\right.$$
$$-k_\psi\cdot\sum_{i=1}^{6}C_{\delta i}\cdot\psi_{k-1}(s-r_{\delta i})-$$
$$\left.-k_\psi^{'}\cdot\sum_{i=1}^{6}C_{\delta i}\cdot\psi_{k-1}(s-r_{\delta i})\cdot(s-r_{\delta i})\right]; \quad (16)$$
$$w_{zk}(s)=\frac{P(s)}{Q_k(s)};\ \psi_k(s)=\psi_g(s)\cdot w_{zk}(s)=$$
$$=w_{zk}(s)\cdot d/s;\ k=\overline{1,n},$$

where the index k is the number of the iteration step, $Q_0(s)$ is the denominator of the TF (13), in which the disturbance is not considered.

At each step of the iteration, an array N of l rows and two columns is created, in which the values of CP $Q_k(s)$ are entered, where the argument s varies in a range sufficient to calculate the passage of the APFC in the vicinity of the critical point according to the Nyquist stability criterion. By processing this array with the use of MLS (l equations with three unknown coefficients of the CP), the current coefficients q_{2k}, q_{1k}, q_{0k} of the CP and, accordingly, the values η_{2k}, f_{2k} are determined.

The number of iteration steps n depends on the results of checking the achievement of the specified value of the difference of the modules selected to control the convergence of the values at the current and previous step, for example $|f_{2k}-f_{2k-1}|$ or $|\eta_{2k}-\eta_{2k-1}|$.

The result of the performed iterations is the indicator η_2 of the stability margin on the CP roots plane and TF (9) of the closed system

$$w_z(s)=\frac{P(s)}{q_2\cdot s^2+q_1\cdot s+q_0}, \quad (17)$$

which is necessary to determine the indicators of the stability margin according to the Nyquist criterion. These indicators are based on the TF of the system open at point A (Fig. 1),

$$w(s)=\frac{w_z(s)}{1+w_z(s)}=\frac{P(s)}{q_2\cdot s^2+q_1\cdot s+q_0+P(s)}=\frac{P(s)}{Q_a(s)}, \quad (18)$$

taking into account the location of the polynomial $Q_a(s)$ roots.

The formulation of the Nyquist criterion depends on the number of polynomial $Q_a(s)$ roots in the right half of the complex plane.

For example, when one of the roots is located in the right half of the plane, then the CS is stable, if in the frequency interval from zero to infinity the critical point K in this criterion is semi-encircled by the open system's curve of APFC

$$w(j\omega)=\frac{P(j\omega)}{Q_a(j\omega)}=u(\omega)+j\cdot v(\omega), \quad (19)$$

where the polynomials P, Q_a are represented in formulas (14, 17, 18).

Indicators of stability margin in terms of amplitude η_a and phase η_{ph} are determined based on the APFC of the open system (19).

The peculiarity of the application of the torque of the CS executive device to the rocket body is that the model

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parameter $a_{\psi\delta}$ (1) is less than zero, therefore, unlike the classical version of the Nyquist stability criterion, the coordinates of the critical point on the plane $u\ jv$ are as follows: $[+1 \quad j \cdot 0]$.

The margin of stability by amplitude η_a is the distance from the point K to the point S of intersection of the APFC (19) and the circle of unit radius with the center O of the plane $u\ jv$, and the margin of stability by phase η_{ph} is the angle's value between the axis Ou and the vector **OS** (Fig. 2).

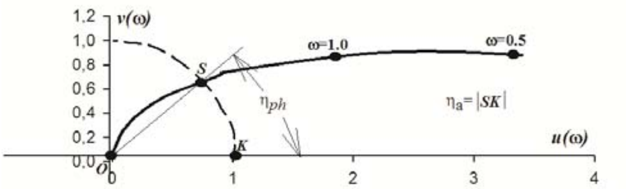

Figure 2 – Margin of stability by amplitude and by phase

The named indicators of the margin of stability are not independent, the relationship between them is determined by the following ratios:

$$\eta_a = \sqrt{2 \cdot (1 - \cos \eta_{ph})}\ ,\ \ \eta_{ph} = \arccos(1 - \frac{\eta_a^2}{2})\ ,$$

which can be used for additional control of the obtained results.

The choice between η_a and η_{ph} in the process of studying the system's dynamic characteristics depends on the specific task.

To calculate the described indicators of the stability margin of the CS on the selected trajectory interval, the following data are required:

– constant components of the model parameters (1) $\bar{a}_{\psi\psi}, \bar{a}_{\psi\delta}$;

– coefficients of approximation of variable component of the model parameters by the sum of exponential functions (3, 6)

$$C_{\psi i}, r_{\psi i,}\ C_{\delta i}, r_{\delta i,}\ i = \overline{1,6};$$

– the preset values of the stability margin η_1 on the plane of the CP $Q(s)$ roots and the frequency f_1 of the rocket body oscillations in the transient process of the disturbance compensation.

The results of the calculations should be:

– LC coefficients (5) k_ψ, k'_ψ;

– values of the stability margin η_2 on the CP $Q(s)$ roots plane and the frequency f_2 of the rocket body oscillations in the transient process of the disturbances compensation;

– indicators of the stability margin of the CS by amplitude η_a and by phase η_{ph}.

Bringing these indicators closer to the desired values can be ensured by correcting η_1, f_1 or characteristics of the CS executive device.

4 EXPERIMENTS

The purpose of the experiments is to verify the described methodological support for the construction of the algorithm for determining the indicators of the CS stability margin on the example of the trajectory section of the rocket first stage, where the deviations of the model parameters from their average values can be 40%.

On this trajectory section, the variable components of the model parameters in the equation (1) are approximated by the sum of exponential functions (3, 6), the coefficients of which and exponents are given in the Table 1.

Table 1 – Approximation coefficients of the model parameters variable components

i	$r_{\psi i}$	$C_{\psi i}$	$r_{\delta i}$	$C_{\delta i}$
1	0.14149	5365	0.04742	–2.836
2	0.14266	–17210	0.06852	10.296
3	–0.30716	11.781	0.00621381	0.565
4	0.14383	24170	0.1209	0.0661
5	–0.31185	–11.579	0.5	$-4.3 \cdot 10^{-9}$
6	0.14445	–12320	0.07312	–8.017

According to the sequence of the described actions, the following data are also required to build the algorithm for calculating the indicators of the stability margin of the rocket rotational motion control system in one plane:

– constant components $\bar{a}_{\psi\psi}, \bar{a}_{\psi\delta}$ of the model parameters in the equation (1);

– preset values of the stability margin η_1 on the plane of the CP roots and the frequency f_1 of the rocket body oscillations in the transient process of the disturbance compensation.

For the selected trajectory section, the coefficients CL k_ψ, k'_ψ are determined according to (15) with two variants of the previous values of the stability margin η_1 (Table 2).

Table 2 – Data for calculation of LC coefficients

$\bar{a}_{\psi\psi}$	$\bar{a}_{\psi\delta}$	η_1	f_1
s^{-2}		s^{-1}	Hz
0.849	–0.331	1.2	0.3
		0.5	

The experiments were carried out in the Mathcad environment, in which the following data determination procedures were used:

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– polyroots(q) – the roots of the polynomial whose coefficients are entered in the array q;

– angle(a,b) – the angle between the abscissa axis and the vector with coordinates *a*, *b*;

– Minimize(f,x) – argument ***x***, at which the function ***f(x)*** is minimal;

– Re(f), Im(f) – real and imaginary component of the complex function *f*.

The main procedures that were necessary for the operation of the algorithm are as follows:

– fm(l,a,b,Q) – entry into the array *l* values of the argument *x* in the range *a...b* and the corresponding values of the function *Q(x)*. By processing this array using MLS, it is approximated by a polynomial of a given degree;

– fq(l,mq) – calculation of the coefficients q_0, q_1, q_2 of the polynomial *Q* (16) by processing array mq of *l* rows using the MLS, which is also filled by the fm procedure:

$$\begin{bmatrix} q_0 \\ q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} l & \sum_{i=1}^{l} s_i & \sum_{i=1}^{l} s_i^2 \\ \sum_{i=1}^{l} s_i & \sum_{i=1}^{l} s_i^2 & \sum_{i=1}^{l} s_i^3 \\ \sum_{i=1}^{l} s_i^2 & \sum_{i=1}^{l} s_i^3 & \sum_{i=1}^{l} s_i^4 \end{bmatrix}^{-1} \cdot \begin{bmatrix} \sum_{i=1}^{l} Q(s_i) \\ \sum_{i=1}^{l} s_i \cdot Q(s_i) \\ \sum_{i=1}^{l} s_i^2 \cdot Q(s_i) \end{bmatrix};$$

– ψf(s,q_0,q_1,q_2) – determination at the current step of the iteration of the image of the CS output signal depending on the complex argument *s* and the coefficients of the polynomial *Q* (12, 16) under the action of the disturbance $\psi_g(t) = 1(t)$,

$$\psi f(s, q_0, q_1, q_2) = \frac{P(s)}{(q_2 \cdot s^2 + q_1 \cdot s + q_0) \cdot s}; \qquad (20)$$

– Qd(s,ψ_{cur}) – calculation of the value of the component of the polynomial *Q* (16), which is due to the instability of the model parameters, depending on the coefficients q_{0k}, q_{1k}, q_{2k} of the function ψ_{cur} (20) at the current iteration step;

Q(s,ψcur) – calculation of the CP value (16) at the current iteration step:

$$Q(s, \psi_{cur}) = s^2 - \bar{a}_{\psi\delta} \cdot k_{\psi}^{'} \cdot s - \bar{a}_{\psi\psi} - \\ -\bar{a}_{\psi\delta} \cdot k_{\psi} - Q_d(s, \psi_{cur});$$

– *u*(ω), *v*(ω) – the real and imaginary component of the APFC of the open system according to (18):

$$u(\omega) = \frac{\mathrm{Re}(w_z(j\omega)) + |w_z(j\omega)|^2}{1 + 2\,\mathrm{Re}(w_z(j\omega)) + |w_z(j\omega)|^2},$$

$$v(\omega) = \frac{\mathrm{Im}(w_z(j\omega))}{1 + 2\,\mathrm{Re}(w_z(j\omega)) + |w_z(j\omega)|^2};$$

– f1(ω) – function for calculation using the Minimize(f_1,ω) procedure of the frequency ω_1, at which the APFC crosses a circle of unit radius:

$$f_1(\omega) = \left| u(\omega)^2 + v(\omega)^2 - 1 \right|;$$

– $\eta_a(\omega_1)$, $\eta_{ph}(\omega_1)$ – formulas for calculating the stability margin according to the Nyquist criterion by amplitude and by phase:

$$\eta_a(\omega_1) = \sqrt{\left[(u(\omega_1) - 1)^2 + v(\omega_1)^2 \right]},$$

$$\eta_{ph}(\omega_1) = \mathrm{angle}(u(\omega_1), v(\omega_1)).$$

Experiments with the use of the above tools made it possible to verify the possibility of using the sequence of actions described in section (3) to determine indicators of the CS stability margin at the selected trajectory section.

5 RESULTS

The advantage of representing the variable components of the model parameters as a sum of exponential functions is a simple transition from the CS differential equations (8) to their Laplace transformation, and the disadvantage is that iterations are necessary to obtain the TF. This can be seen from equation (10), in which the image ψ(s) of the CS output signal is included in the terms of the left part of the equation, which are due to the instability of the parameters.

The convergence of the iterative process of determining the instability influence of the model parameters on the stability margin η for the selected data example and two variants of the initial value η_1 is shown in Tables 3, 4.

In the third and fourth columns of the Tables 3, 4 are shown fragments of the array N in which *l* values of CP $Q(s_i)$ are entered in the range of arguments sufficient to establish the position of the APFC of the open system relative to the critical point in the Nyquist criterion. Processing of this array using MLS gives the coefficients and roots of CP (16) after the current iteration step.

As follows from these Tables, for the selected data example, three iterations are enough so that the indicator η_2 of the CS stability margin, considering the instability of the model parameters, was calculated with an error of no more than 0.01 s^{-1}.

As is known, to calculate the parameters of the stability margin by amplitude η_a and by phase η_{ph} based on the Nyquist criterion, the APFC $w(j\omega)$ of the open system (19) is needed in the vicinity of the frequency range ω, in which its passage relative to the critical point with coordinates $[+1 \quad j \cdot 0]$ on the plane $u \; jv$ is determined.

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Table 3 – Convergence of iterations at $\eta_1 = 1.2\ s^{-1}$

k	i	s_i	$Q_k(s_i)$	η_2	$\eta_{2k}-\eta_{2\,k-1}$
1	1	0.4	3.01972	0.9064601	–0.2935395
	2	0.73043	5.3342038		
	3	1.06087	6.5131834		
	.	…..	…..		
	l	8	82.30107		
	q_{21}		q_{11}	q_{01}	
	1.00444		1.82097	3.47350	
2	1	0.4	4.4387594	0.9059249	$-5.35\cdot10^{-4}$
	2	0.73043	5.3424195		
	3	1.06087	6.5218544		
	.	…..	…..		
	l	8	82.3035688		
	q_{22}		q_{12}	q_{02}	
	1.00446		1.81992	3.48263	
3	1	0.4	4.4386312	0.9059502	$-2.53\cdot10^{-5}$
	2	0.73043	5.342307		
	3	1.06087	6.5217596		
	.	…..	…..		
	l	8	82.3035647		
	q_{23}		q_{13}	q_{03}	
	1.00445		1.81997	3.48250	

Table 4 – Convergence of iterations at $\eta_1 = 0.5\ s^{-1}$

k	I	s_i	$Q_k(s_i)$	η_2	$\eta_{2k}-\eta_{2\,k-1}$
1	1	0.4	3.01972	0.3665767	–0.1334233
	2	0.73043	3.5782648		
	3	1.06087	4.4027546		
	.	…..	…..		
	l	8	72.5998937		
	q_{21}		q_{11}	q_{01}	
	1.00346		0.73569	2.51093	
2	1	0.4	2.679288	0.2033659	–0.1632108
	2	0.73043	3.1218419		
	3	1.06087	3.8378597		
	.	…..	…..		
	l	8	69.8009891		
	q_{22}		q_{12}	q_{02}	
	1.00446		1.81992	3.48263	
3	1	0.4	2.6741968	0.2046855	0.0013196
	2	0.73043	3.120315		
	3	1.06087	3.8388745		
	.	…..	…..		
	l	8	69.8023279		
	q_{23}		q_{13}	q_{03}	
	1.00376		0.41091	2.29259	

Table 5 – Indicators of the CS stability margin

η_1	η_2	η_a	η_{act}	η_{ph}	η_{phct}
s^{-1}		–		degrees	
1.2	0.906	0.717	0.842	42.0	49.8
0.5	0.205	0.174	0.414	10.0	23.9

The formulation of the criterion depends on the roots of the CP of the open system, which can be determined, for example, by the Minimize procedure in the Mathcad environment. For the data example in the Tables 1, 2 and η_1=1.2 s^{-1} they are equal to –0.963 and +1.075, i.e. one of the CP roots is in the right half of the roots plane. Therefore, according to the Nyquist criterion, the CS stability takes place under the condition that the curve of the APCH (19) is in the range frequency ω from zero to infinity (Fig. 2) makes a semicircle above the critical point $\boldsymbol{K}$ with coordinates $[-1\ j\cdot 0]$.

The calculations performed according to the described algorithm show that the instability of the model parameters for the data example (Tables 1, 2) at η_1=1.2 s^{-1} leads to a decrease of the stability margin in comparison with the results of the method of frozen coefficients for the selected trajectory section on the CP roots plane (16) by approximately 25% and, according to the Nyquist criterion, the stability margin in term of amplitude by 15%, in term of phase by 16%.

Since the relationships between the named indicators are not described by linear functions, the ratios between them in quantitative terms do not coincide.

When η_1=0.5 s^{-1} the indicators of the stability margin on the CP roots plane decrease by approximately 59%, and according to the Nyquist criterion, the stability margin in terms of amplitude and phase decreases by 58% (Table 5).

The experiment results show the possibility of building an algorithm for calculating the stability margin indicators of a time-varying CS on a selected trajectory section obtaining an equivalent stationary CS using the Laplace transformation of the model parameters time-varying components given by the sum of exponential functions.

6 DISCUSSION

To use the described actions in the design work for the construction of the algorithm for calculating the stability margin indicators, it is necessary given by tables or graphs of the dependence of the model parameters on time. The flight path is divided into sections, on each of which are determined coefficients of approximation of the model parameters variable components by the sum of exponential functions.

Based on the CO characteristics and the CS executive device, the desired values of the CP roots are assigned.

The Laplace transformation of the variable components of the model parameters makes it possible to move from a differential equation with time-varying coefficients to a TF, which matches LTV with an equivalent stationary system on a selected trajectory section.

The proposed approach to determining the stability margin indicators of time-varying CS has the advantage that their error is the same for all points of the selected trajectory section, while when using the method of frozen coefficients, the error depends on the distance to the middle point of the trajectory section. This can give a possibility of increasing the size of the trajectory sections and, accordingly, reducing their number.

CONCLUSIONS

The scientific novelty of the work consists in the development of a methodology for determining the indicators of the margin of stability of a time-varying rotary motion control system of a rocket by means of Laplace transformation of the variable component of the mathematical model parameters given by the sum of exponential functions.

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The practical significance of the obtained results is the expansion of the methodological basis for the design rocket motion control systems.

Prospects for further research is to assess the complexity level of the algorithm taking into account the inertia of the executive device and the disturbed movement of the mass center.

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ЗАПАС СТІЙКОСТІ НЕСТАЦІОНАРНОЇ СИСТЕМИ УПРАВЛІННЯ ОБЕРТАЛЬНИМ РУХОМ РАКЕТИ

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АНОТАЦІЯ

Актуальність. Система управління рухом ракети є нестаціонарною, оскільки в процесі польоту її параметри залежать від точки траєкторії і витрат палива. Показники запасу стійкості визначають в обмеженому околі окремих точок траєкторії з використанням алгоритмів, які розроблені тільки для лінійних стаціонарних систем, що призводить до необхідності введення коефіцієнтів запасу в апаратних засобах. В доступних джерелах розробці методів визначення кількісної оцінки запасу стійкості нестаціонарної системи управління належної уваги не приділяється.

Мета роботи – розробка методичного забезпечення побудови алгоритму розрахунку показників запасу стійкості нестаціонарної системи управління обертальним рухом ракети у площині рискання з використанням на вибраних дільницях траєкторії еквівалентного стаціонарного наближення.

Метод. Математична модель системи управління обертальним рухом ракети в одній площині прийнята у вигляді лінійного диференційного рівняння без врахування інерції виконавчого пристрою та інших збурювальних факторів. Ефект відхилення параметрів від їх середніх значень для певної дільниці траєкторії розглядається як збурення, що дає можливість переходу від нестаціонарної моделі до еквівалентної наближеної стаціонарної. Для оцінки показників запасу стійкості використаний критерій Найквіста, що спирається на аналіз частотної характеристики розімкненої системи, для визначення якої використовується математичний апарат перетворення Лапласа. З метою спрощення переходу від функцій часу у диференційному рівнянні збуреного руху до функцій комплексного змінного у перетворенні Лапласа змінні у часі параметри моделі подані у вигляді суми експоненціальних функцій.

Результат. Розроблене методичне забезпечення для побудови алгоритму визначення запасу стійкості системи управління обертальним рухом ракети на заданій дільниці траєкторії з непостійними у часі параметрами.

Висновки. На прикладі нестаціонарної системи управління обертальним рухом ракети показана можливість використання перетворення Лапласа для визначення показників запасу стійкості.

Отримані результати можуть бути використані на початковому етапі проектних робіт.

Наступний етап дослідження це оцінка рівня складності алгоритму при врахуванні інерції виконавчого пристрою та збуреного руху центру мас.

КЛЮЧОВІ СЛОВА: управління рухом ракети, лінійна нестаціонарна система, перетворення Лапласа.

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DEVELOPMENT OF AUTOMATED CONTROL SYSTEM AND REGISTRATION OF METAL IN CONTINUOUS CASTING

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ABSTRACT

Context. Modern industrial enterprises face challenges that require introduction of latest technologies to improve efficiency and competitiveness. In metallurgy, one of key stages is continuous casting, where quality of products and economic performance of enterprise depend on accuracy and efficiency of process control. Products made using continuous casting technology are widely used in various industries due to their high mechanical properties, structural uniformity and cost-effectiveness.

The development of automated metal management and registration system is becoming not only relevant, but also necessary to ensure stable and efficient production.

The problem of improving quality of metal products has always been one of most important tasks in steel industry. Imperfect technological processes, human error and equipment malfunctions can lead to defects in finished metal products. This, in turn, affects final characteristics of products, their durability and reliability.

To date, available sources have not yet found complete solution to this problem. Therefore, it is necessary to formulate problem and develop algorithm for operation of automated system for controlling and registering metal in continuous casting.

Objective. The goal of work is to develop automated metal management and registration system to improve quality of metal products.

Method. To achieve this goal, parametric model was proposed, which is formalized on basis of set theory. The model takes into account key parameters of continuous casting process: material characteristics, structural features of crystallizer, casting modes, metal level in crystallizer, and position of shot stopper.

Results. The problem was formulated and key parameters were determined, which are taken into account in system's algorithm, which made it possible to develop system for controlling parameters of continuous casting to solve problem of improving quality of metal products.

Conclusions. To improve quality of metal products and stability of casting process, parametric model was created that is comprehensive, allows optimization of key parameters and ensures accuracy of process control by integrating not only modes of product formation, but also takes into account specific properties of source material (chemical composition of material grade, etc.) and design features of casting plant. Algorithm for automated control system has been developed that takes into account relationships between certain key parameters and ensures optimal control of casting process. Based on proposed complex parametric model and algorithm, automated control and metal registration system was created. The focus of work is on quality and efficiency of metal management and registration in continuous casting, based on modern methods of computer science and engineering. A comprehensive experimental comparison of developed system with commercial analogs in real production conditions was carried out, which allowed us to objectively assess its efficiency and reliability.

KEYWORDS: automation, system, parametric model, control, registration, metal.

ABBREVIATIONS

AI – analog input;
ALOG – alarm log block;
CC – continuous casting;
CCM – continuous casting machine;
IL – industrial ladle;
GE – graphic element;
MP – metal products;
ONF – on/off control block;
PLC – programmable logic controller;
SCADA – supervisory control and data acquisition;
SL – steel ladle;
SP – stopper;
STC – steel ladle;
TMR – temperature.

NOMENCLATURE

A is a wall A of crystallizer;

${A^d}_i$ is a distance from wall A of crystallizer to opposite wall (bottom), m;

A_i^{rc} is a vibration amplitude of crystallizer, mm;

${A^{up}}_i$ is a distance from wall A of crystallizer to opposite wall (top), m;

B is a wall B of crystallizer;

${B^d}_i$ is a distance from wall B of crystallizer to opposite wall (bottom), m;

B_i is a grade of material (metal);

${B^{up}}_i$ is a distance from wall B of crystallizer to opposite wall (top), m;

Ch_{mi} is a chemical composition of material grade;

CM_i is a casting modes;

D_{bwi} is a distance between opposite walls at top and bottom of crystallizer, m;

DF_i is a design feature of crystallizer;

$[E]_i$ is a average dissolved element content in steel, %;

G_{Cci} is a metal consumption in crystallizer;

G_{Cd_i} is a metal consumption from steel ladle;

G_{CId_i} is a metal consumption from industrial ladle;

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H_{cri} is a height of crystallizer, m;

h_i^{cr} is a metal level in crystallizer, m;

h_i^{Idl} is a metal level in industrial ladle, m;

h_i^{l} is a metal level, m;

h_i^{ls} is a slag level, m;

h_i^{Stl} is a metal level in steel ladle, m;

$h^{uf}{}_i$ is a amount of underfilling of liquid metal to top of copper sleeve of crystallizer, m;

$h^{w}{}_{cri}$ is a working (active) height of crystallizer, m;

I is a number of possible alternatives;

$k^{c}{}_i$ is a hardening rate, mm/min ^{½};

k_v is a coefficient of workpiece pulling speed;

M_i is a material (metal);

$M^{rc}{}_i$ is a mechanism of rocking crystallizer;

$N^{rc}{}_i$ is a number of crystallizer vibrations;

$P^{hc}{}_i$ is a position of hydraulic cylinder rod;

$P^{vl}{}_i$ is a valve position;

q_i is a metal casting speed;

$Sh^{rc}{}_i$ is a shape of crystallizer vibrations;

SP_i is a position of locking mechanism;

Spl is a plane of stopper outlet, m^2;

T_{CCi} is a temperature modes, °C;

$T^{h}{}_{SCZ\,i}$ is a temperature of hardened steel at end of secondary cooling zone, °C.

T_i is a type of material (type of metal);

$T^{ild}{}_i$ is a metal temperature in industrial ladle, °C;

$T^{ild}{}_i$ is a metal overheating temperature in industrial ladle, °C;

$T^{ld}{}_i$ is a metal temperature in steel ladle, °C;

$\Delta T^{ld}{}_i$ is a metal overheating temperature in steel ladle, °C;

T_{liqi} is a liquidus temperature of continuous casting, °C;

$T^{p}{}_{sm}$ is a solidification temperature of pure iron, °C;

$T^{s}{}_{SCZ\,i}$ is a surface temperature of workpiece in *i*-th section of secondary cooling zone, °C;

$T^{wpc}{}_i$ is a temperature of crystallizer working surface, °C;

$\Delta t^{liq}{}_{Ei}$ is a amount of decrease in solidification temperature of iron when 1 % of corresponding element is introduced into it, °C;

α is a coefficient for calculating distance between opposite walls in crystallize;

μ is a consumption factor that depends on viscosity of liquid steel grade being poured;

$\rho^{m}{}_i$ is a material density, t/m^3;

$\tau^{c}{}_i$ is a curing time, min;

$\tau^{cr}{}_i$ is a length of time material stays in crystallizer;

ν_i^{rc} is a vibration frequency of crystallizer, min^{-1};

$\nu^{wcr}{}_i$ is a working speed of workpiece pulling, m/min.

INTRODUCTION

The use of metal products is extremely relevant in modern world, as metal has become main material for construction of complex and durable structures in construction, engineering, and other industries [1–3].

Metal products are characterized by high strength, resistance to wear and corrosion, durability and ability to be used in various operating conditions. In addition, metal products are efficient in recovery processes and can be recycled, making them environmentally sustainable. One of most important processes in production of metal products is continuous casting.

CC technology is used to produce wide range of metal products, including steel bars, aluminum blocks and other complex structures. It automates molding process and ensures high product quality stability through precise control of casting parameters.

Controlling and accurately recording process parameters remain challenging tasks that affect quality and stability of production. Shortcomings in control systems can lead to reduced product quality, losses, and even accidents. Therefore, solving these problems is urgent task to improve efficiency and reliability of continuous casting process.

Automated control makes it possible to precisely control process parameters such as temperature and metal casting speed, ensuring stable production conditions and preventing defects. In addition, automated system records data in real time, which simplifies maintenance of process documentation and allows for quick response to changes in process parameters.

The research tasks include development of parametric model of continuous metal casting process that will not only control process of forming metal products, but also take into account unique properties of source material and design features of casting plant. In addition, it is necessary to identify and analyze modern methods of controlling casting parameters, develop algorithm for automatic process control to optimize productivity and product quality, and implement system. These tasks are aimed at creating and implementing advanced technologies to improve continuous metal casting process. Practical tasks include implementation of algorithm and creation of automated control system for continuous casting process, implementation of real-time or scheduled process parameter recording.

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Since one of main challenges in metal forming is to improve quality of products and obtain products with high material properties. These aspects are critical to ensuring competitiveness in market and meeting requirements of modern quality standards, which is why we have chosen this topic for our research.

The initial data include results of previous studies, technical requirements for creation of automated control system [1–3]. The introduction of automation into continuous casting process by providing system with tools for controlling and recording casting parameters, optimizing production modes based on specific requirements and material properties are important tasks.

The object of research is process of control and registering metal in crystallizer.

The subject of research is continuous casting unit, or more specifically, crystallizer.

The purpose of the research is development of automated metal management and registration system to ensure quality of finished metal products.

1 PROBLEM STATEMENT

The modern steel industry is facing numerous challenges, including need to improve product quality and process stability. Continuous metal casting is critical stage in production cycle where precise parameter control and process optimization are crucial. Failure to properly control and record casting parameters can lead to defects in finished products, reduced productivity, and increased production costs.

Modern production processes are characterized by high complexity and dynamism. There is need to develop universal approaches to creating adaptive control systems that can function effectively under conditions of uncertainty and variable parameters. The key problem is development of mathematical models and algorithms that would ensure optimal control in real time.

Given all these challenges and needs of modern steel industry, it is clear that current management and control methods need to be improved to meet the growing demands on production efficiency and quality. The complexity of processes, dynamic parameters and high requirements for final product require introduction of new solutions that take into account all aspects of production cycle and provide optimal control in real time. Therefore, there is urgent need to develop automated metal management and registration system that will ensure high quality products and process stability.

The mathematical formulation includes creation of parametric model that takes into account material characteristics and specifics of production process to improve quality of metal products.

Input data for system includes crystallizer configurations and properties, as well as material parameters and casting modes.

A parametric model is proposed that formalizes key parameters for specific casting process and is necessary both for design of new plants and for existing units to optimize process of molding MP.

The input parameters for development of automated control system for MP unit are represented by model:

$M_i =< T_i, B_i, \rho^m{}_i, Ch_{mi} >,\ i=1,\ 2,\ ...,I;$

$DF_i = \ < D_{bwi}, H_{cri}, h^w{}_{cri}, h^{uf}{}_i, M^{rc}{}_i >,\ i=1,\ 2,\ ...,I;$

$M^{rc}{}_i =< N^{rc}{}_i,\ \nu_i^{rc}, A_i^{rc}, Sh^{rc}{}_i >;\ i=1,\ 2,\ ...,I;$

$CM_i = \ < T_{CCi}, q_i, \tau^{cr}{}_i,\ v^{wcr}{}_i, k_v,\ \tau^c{}_i, k^c{}_i >,$
$i = 1,\ 2,\ \ldots, I;$

$T_{CCi} = \ < T^{ld}{}_i, \Delta T^{ld}{}_i, T^{ild}{}_i, \Delta T^{ild}{}_i, T^{wpc}{}_i, T_{liqi}, T^s{}_{SCZi}, T^h{}_{SCZi} >,$

$i=1,\ 2,\ ...,I;\ \ T_{liqi} =< T^p{}_{sm},\ [E]_i, \Delta t^{liq}{}_{Ei} >,$

$i=1,\ 2,\ ...,I;\ \ D_{bwi} =< A^{up}{}_i, A^d{}_i, B^{up}{}_i, B^d{}_i >;$
$i=1,\ 2,\ ...,I.$

The distance between opposite walls:
$A^{up}{}_i = (1,04\ \ldots 1,05) \times \alpha;$ $B^{up}{}_i = (1,02\ \ldots 1,03) \times \alpha;$

$A^d{}_i = (1,03\ \ldots 1,04) \times \alpha;$

$B^d{}_i = (1,01\ \ldots 1,02) \times \alpha;\ SP_i = \ < P^{hc}{}_i, P^{vl}{}_i >,$

$G_{Cd_i} =< Spl, h_i^l, h_i^{ls}, h_i^{Stl}, \mu >;$ $i=1,\ 2,\ ...,I;$

$G_{CId_i} =< Spl, h_i^l, h_i^{ls} >;\ i=1,\ 2,\ ...,I.$

As result, it is planned to obtain parametric model that will be implemented in developed automated system, which will further improve quality of metal products through accurate and stable control of casting parameters.

2 REVIEW OF THE LITERATURE

The continuous metal casting process and its control are actively studied in numerous scientific papers, with main focus on technological aspects and automation systems. The literature review of this process focuses on its efficiency, technical solutions, and innovations in controlling production parameters.

Authors of [4] describe continuous casting process, which has become main method of steel production since mid-1980s, replacing traditional ingot casting method. The authors emphasize high productivity, quality, and energy efficiency of continuous casting, as well as importance of research and development in this area to meet growing demands on steel quality, energy efficiency, and environmental aspects.

Technological aspects are described in detail in [5–8].

In [5] provides historical overview of casting methods used to produce steel sheets for various applications. The article analyzes advantages and disadvantages of modern casting methods.

In [6] analyzes machine learning methods for monitoring and controlling continuous steel casting process. The authors describe challenges, possible solutions, and future research directions in this area.

In [7], basic metallurgical principles of casting technology are discussed in detail. The authors analyze prop-

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erties of metals: cast iron, cast steel, and cast non-ferrous alloys.

In [8], we are talking about technology of two-phase zone continuous casting. The authors model flow and temperature fields at different speeds.

Quality is critical in casting, as it determines quality of final product and its properties that affect its further use in industry [9–11].

In [11], attention is focused on improving continuous casting process in steel production by optimizing design parameters of submerged casters. The authors link quality of slab production to casting mold and casting flow patterns. The study presents new optimization method called African buffalo algorithm, which was implemented in Matlab to optimize parameters such as nozzle size, port shape, length, immersion depth, etc. The authors also take into account fluid flow rate, however, they do not pay attention to specific properties of source material that directly affect process and quality of final product. In our work, one of things we plan to do is to take into account chemical composition of material grade, which affects: hardness and strength of steel, as well as melting point; improve corrosion resistance, strength, and other mechanical properties; defects in metal, such as cracks or pores.

In [12], quantification of degree of defects in continuously cast billets is presented in YOLOv5. The authors proposed network that solves problems associated with noise or dirty spots and different sizes of defects in images of these workpieces. Although innovative networks have been introduced in work, design features of casting plant, which also affect quality of resulting metal products, have not been taken into account.

In [13] discusses defects in continuous casting of steel billets and their impact on quality of finished products. The authors determined that occurrence of defects depends on temperature distribution and cooling regime in casting gating. Although authors paid attention to chemical composition of melt and secondary cooling modes, they again did not take into account design features of casting equipment. The article also notes that solutions used on one casting gating may not always be applicable to other gating due to different conditions.

Recent years have shown growing interest in new methods of monitoring and controlling this complex process, such as MP, which is reflected in work on development of automated systems based on modern technologies such as machine learning, artificial intelligence, etc. Therefore, automated systems are and will remain key area for improving quality and efficiency of metal production.

In [14] describes design of PLC-based control system for continuous casting machine. The authors use sensors to collect information about actual state of slab and then transfer it to PLC. This allows for real-time monitoring of slab quality, increasing level of automation of continuous casting process, production efficiency, and cost-effectiveness. The work also describes structure of automatic control system, which includes control, monitoring, and control levels. The authors discuss in detail various components of system, such as ladle turret, intermediate ladle slide gate control, electro-hydraulic servo system, crystallizer cooling water control, and crystallizer vibration system. The main goal of development is to increase level of automation of continuous casting process, improve quality of castings, and increase productivity. While article has concrete results, however, despite emphasis on automation, article emphasizes limited possibilities of manual control in emergency situations, which can pose potential risk to safety and reliability of process. This emphasizes need for balance between automation and possibility of manual intervention in critical situations.

References [15–17] provide overview of modern technologies and automation systems used in continuous casting processes.

In field of metals continuous casting, these works highlight key aspects that arise in process of manufacturing finished metal products.

The general trend of these scientific papers is great interest in continuous casting technologies, disclosure of issues related to quality of finished products made of metals obtained by casting. The issue of designing control system for continuous casting machine. These works cover important aspects, such as introduction of new methods for controlling parameters of continuous casting process, quantifying degree of defects, etc.

Therefore, this work focuses on control and registration of metal during continuous casting with possibility of manual control of most important parameters of MP process, which are taken into account in parametric model, if necessary, which is prerequisite for improving quality of resulting metal products.

3 MATERIALS AND METHODS

Investigate process develop comprehensive parametric model of CC.

To address key challenge of developing mathematical models and algorithms for real-time optimal control and achieving goal, our study of continuous casting process proposes parametric model. This model captures key aspects of this complex process, providing framework for optimizing control. The development of such parametric models is critical for technology improvement in various fields of science and industry [9, 18], including continuous casting, where it allows for effective real-time optimal control problems.

Moreover, definition and formalization of molding process parameters creates basis for further development of intelligent decision support systems that can integrate machine learning and big data analysis. This opens up new opportunities for use of advanced information technologies in industrial production.

The proposed model accurately reflects relationships between various parameters that affect quality and efficiency of CC production.

The necessary and sufficient parameters are represented in complex form as tuple of parameters:

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$$CC =< M_i, DF_i, CM_i, SP_i, G_{Cdi}, G_{CIdi}, G_{Cci} > . \quad (1)$$

In course of study, parametric model describing forming of metal products was created. This model is presented comprehensively as set of interrelated parameters that cover not only direct modes of molding process, but also take into account specific properties of source material. In addition, model integrates design features of casting equipment, including characteristics of crystallizer and configuration of locking mechanism.

The ultimate goal of project is to develop automated system based on created parametric model. This system is designed to efficiently manage process and accurately account for metal at forming stage of metal products. It will optimize production process, improve product quality and ensure efficient use of resources.

Describe selection and description of main parameters of metal forming process.

In this work, term «molding process» refers to process of continuous metal casting.

The selection and description of metal forming process key parameters is not only important step in solving applied problems in metallurgy, but also significant contribution to development of information technology and complex process control systems.

Our approach to decomposing complex technological process into local object-zones and identifying key control parameters demonstrates innovative method of formalizing and structuring data to create effective information models. This makes it possible to develop more accurate forecasting and optimization algorithms, which is urgent task in field of computer science.

We propose decomposition of complex technological process of molding into local objects-zones:

1) steel ladle area;
2) industrial ladle area;
3) primary cooling zone (crystallizer).

Next, let's define key control parameters that affect both metal level and quality of MP at stage of metal billet molding.

Deviations from optimal casting mode caused by various factors can lead to decrease in productivity, deterioration in metal quality, and occurrence of emergencies.

So, based on analysis of molding process, parameters and values they can take have been determined, and we will formalize these parameters below.

The first parameter is temperature of metal in industrial ladle:

$$T_i^{ild} = \begin{cases} T_1^{ild}, \text{ if } 1753 \le T^{ild} \le 1768, \\ T_2^{ild}, \text{ if } 1763 \le T^{ild} \le 1783, \\ T_3^{ild}, \text{ if } 1793 \le T^{ild} \le 1813, \\ T_4^{ild}, \text{ if } 1803 \le T^{ild} \le 1843, \\ T_5^{ild}, \text{ if } 1793 \le T^{ild} \le 1813, \\ T_6^{ild}, \text{ if } 1798 \le T^{ild} \le 1818. \end{cases} \quad (2)$$

Indexes 1, 2, 3, 4, 5, 6 in parameter T_i^{ild} here and in future – ranges of values for different steel grades: 1 – ШХ15; 2 – Ст50, 3 – Ст20–45, 4 – 12ХН3А, 5 – 40Х, 6 – Ст3сп):

Metal overheating temperature in industrial ladle:

$$\Delta T_i^{ild} = \begin{cases} T_1^{ild}, \text{ if } 1768 \le \Delta T^{ild} \le 1793, \\ T_2^{ild}, \text{ if } 1778 \le \Delta T^{ild} \le 1808, \\ T_3^{ild}, \text{ if } 1808 \le \Delta T^{ild} \le 1838, \\ T_4^{ild}, \text{ if } 1818 \le \Delta T^{ild} \le 1868, \\ T_5^{ild}, \text{ if } 1808 \le \Delta T^{ild} \le 1838, \\ T_6^{ild}, \text{ if } 1818 \le \Delta T^{ild} \le 1843. \end{cases} \quad (3)$$

The value of optimal overheating varies from 15 to 25 °C when pouring melt in closed stream for up to one hour, and in most cases, modern CCMs use closed jet to feed metal into crystallizer with melt pouring duration of no more than 60 minutes.

The second parameter is temperature of metal according to steel ladle (steel ladle is main metallurgical equipment required for receiving, transporting, processing steel in ladle and pouring molten metal):

$$T_i^{ld} = \begin{cases} T_1^{ld}, \text{ if } 1773 \le T^{ld} \le 1818, \\ T_2^{ld}, \text{ if } 1783 \le T^{ld} \le 1833, \\ T_3^{ld}, \text{ if } 1813 \le T^{ld} \le 1863, \\ T_4^{ld}, \text{ if } 1823 \le T^{ld} \le 1893, \\ T_5^{ld}, \text{ if } 1813 \le T^{ld} \le 1843, \\ T_6^{ild}, \text{ if } 1823 \le T^{ild} \le 1848. \end{cases} \quad (4)$$

Metal overheating temperature in steel ladle:

$$\Delta T_i^{ld} = \begin{cases} T_1^{ld}, \text{ if } 1787 \le \Delta T^{ld} \le 1837, \\ T_2^{ld}, \text{ if } 1793 \le \Delta T^{ld} \le 1852, \\ T_3^{ld}, \text{ if } 1827 \le \Delta T^{ld} \le 1852, \\ T_4^{ld}, \text{ if } 1837 \le \Delta T^{ld} \le 1912, \\ T_5^{ld}, \text{ if } 1827 \le \Delta T^{ld} \le 1862, \\ T_6^{ild}, \text{ if } 1837 \le \Delta T^{ild} \le 1867. \end{cases} \quad (5)$$

The third parameter is temperature of crystallizer's working surface:

$$160 \le T^{wpc}{}_i \le 180. \quad (6)$$

According to various estimates based on direct measurements, temperature of crystallizer working surface is

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usually 160–180 °C. The value of this temperature can vary depending on number of factors: thermal conductivity of crystallizer wall material, intensity of heat removal by water, thickness of crystallizer wall, composition and thickness of working coating, etc.

The steel casting rate depends on its temperature in tundish and can be described as follows:

$$2 \le q_i \le 3. \quad (7)$$

The fourth parameter is vibrations amplitude of crystallizer:

$$1 \le A_i^{rc} \le 3. \quad (8)$$

The fifth parameter, vibrations frequency of crystallizer, can be described as follows:

$$0 \le \nu_i^{rc} \le 300. \quad (9)$$

The sixth parameter is level of metal in steel ladle:

$$2.5 \le h_i^{Stl} \le 3. \quad (10)$$

The seventh parameter is level of metal in industrial ladle:

$$0.7 \le h_i^{Idl} \le 1.2. \quad (11)$$

The eighth parameter – position of stopper – is also one of main parameters that needs to be monitored because it is possible to quickly change metal consumption:

$$SP_i = \begin{cases} SP_1, \text{if } SP = [\text{open}], \\ SP_2, \text{ if } SP = [\text{close}]. \end{cases} \quad (12)$$

The ninth parameter is level of metal in crystallizer:

$$0.75 \le h_i^{cr} \le 0.85. \quad (13)$$

The rationale for selecting key control parameters is shown in Table 1.

3.3 Technical means for controlling casting parameters

In context of developing automated control and metal registration system for continuous casting, creation of effective information and measurement subsystem is a key element that requires use of modern computer science methods. This subsystem not only optimizes continuous casting process, but also provides reliable basis for automated control and accurate recording of metal parameters based on modern information technology and data processing methods.

Table 1 – Key parameters of metal CC process control: description, causes and consequences

Description	Reason	Consequences
Temperature of metal in industrial ladle	1) Unstable liquid metal temperature at furnace outlet – initial temperature affects entire casting process. 2) Heat loss during transportation. 3) Thermal insulation properties of industrial ladle. 4) The time metal stays in rolling mill (longer metal stays in rolling mill, more it cools down). 5) Additional heating (use of induction or gas heaters to maintain required metal temperature).	1) Quality of finished products. 2) The stability of CC. 3) Crystallization rate. 4) Equipment wear and tear.
Temperature of metal in steel ladle Temperature of metal in steel ladle	1) Unstable temperature of liquid metal at furnace outlet. 2) Heat loss during transportation. 3) Thermal insulation properties of steel ladle. 4) The time metal stays in ladle. 5) Additional heating. 6) The casting process (speed and uniformity of metal casting can affect temperature control).	1) Quality of finished products. 2) Crystallization process. 3) Productivity of casting process. 4) Equipment wear and tear.
Temperature of working surface of crystallizer	1) Thermal conductivity of crystallizer material. 2) Efficiency of cooling system. 3) Heat load from molten metal. 4) Coolant temperature and thermal processes in crystallizer. 6) Condition of working surface of crystallizer.	1) The process of metal crystallization. 2) Formation of primary crust. 3) Thermal stresses. 4) Wear and tear of crystallizer.
Vibrations amplitude of crystallizer Vibrations frequency of crystallizer	1) Design and characteristics of crystallizer. 2) Casting speed. 3) Viscosity and composition of metal. 4) Temperature affects metal properties, which in turn determines optimal oscillation parameters. 5) The massiveness and size of metal stream can affect optimal oscillation frequency, which ensures uniform cooling and formation of primary crust.	1) Quality of finished products. 2) Formation of primary metal cortex. 3) Smoothness and uniformity of surface of MP. 4) Thermal stresses. 5) Stable casting process, increasing productivity and reducing downtime.

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Continuation of Table 1

Description	Reason	Consequences
Level of metal in steel ladle	1) The rate at which metal is fed from furnace. 2) The rate at which metal flows out of ladle affects maintenance of stable level. 3) The level of metal. 4) The rate at which metal is drained from ladle to tap or other equipment. 5) Metal temperature. 6) Metal level depends on system pressure, which affects flow and spillage of metal.	1) Quality of finished products. 2) Stability of casting process. 3) The correct metal level reduces risk of defects such as sinks and pores.
Level of metal in steel ladle	7) The volume and shape of ladle can affect maintenance of stable metal level.	5) Cooling efficiency, which in turn affects crystallization rate and product quality.
Level of metal in industrial ladle	1) Metal feed rate from steel ladle. 2) The speed of pouring into crystallizer. 3) The temperature of metal affects its viscosity and flow rate, which can change level of metal in industrial ladle. 4) Metal level. 5) The design and dimensions of industrial ladle determine maximum and minimum metal level that can be maintained. 6) The pressure of metal in system affects its flow and, accordingly, level in industrial ladle. 7) The process of draining and filling ladle.	1) Quality of finished products. 2) Stability of casting process. 3) Avoidance of defects such as pores and cracks. 4) Ensuring optimal level of metal allows you to maintain high productivity without stops and interruptions. 5) Efficiency. 6) Equipment wear and tear.
Position of stopper	1) Casting speed. 2) Viscosity and composition of metal. 3) The level of metal in tundish. 4) Metal pressure. 5) Metal temperature. 6) The design and dimensions of stopper and crystallizer can affect precise parameters of metal flow control.	1) Quality of finished products. 2) Metal flow rate. 3) Metal level in crystallizer. 4) Pressure and turbulence of flow. 5) Avoidance of defects – cavities, sinks and cracks. 6) Stability of casting process. 7) Equipment wear and tear.
Metal level in crystallizer	1) Metal feed rate from industrial ladle. 2) The position of stopper. 3) Metal temperature. 4) Efficiency of cooling system of crystallizer. 5) Metal level. 6) Design and dimensions of crystallizer.	1) Quality of finished products. 2) Crystallization process. 3) Thermal stresses. 4) Productivity of casting process. 5) Metal level.

Our automated control system integrates variety of sensors to form comprehensive information network for real-time monitoring, analysis and control of casting parameters. This approach is based on principles of system analysis and information system design, which are key aspects of modern computer science.

Optimal control of casting parameters is critical to guaranteeing high quality of finished MPs and production safety. In this aspect, use of specialized equipment becomes mandatory, with sensors playing key role in such equipment. It is they who make it possible to accurately measure and regulate various characteristics of casting process, which ensures its effective control and management.

To begin with, measurement of metal temperatures in tundish, steel ladle and crystallizer working surface is realized thanks to CEM DT infrared pyrometer, which allows measuring high temperatures in hard-to-reach places. The device is capable of detecting temperatures above 1000 degrees (–50 °C…+1600 °C) at distance of several meters without touching object of study. Sensors can be placed at every critical point of CC process.

The amplitude of vibrations will be measured using sensor 640B01 – vibrations will be measured using sensor 640B01, industrial speed converter. It has following characteristics: speed measurement from 0 to 1 inch/sec (0 to 25,4 mm/sec); output signal from 4 to 20 mA; 2-pin connector. The frequency range for measurement is (± 10 %) from 180 to 60,000 rpm (3 to 1000 Hz).

The vibrations frequency of crystallizer can be measured using digital frequency meter 10–199,9 Hz. This device was chosen because of following characteristics: frequency measurement from 20 to 600 cycles per minute; supported voltage from 80 to 300 V; ability to measure amplitude of vibrations of crystallizer in range from 1 to 50 mm.

The metal level in steel ladle, tundish and crystallizer is monitored using special eddy current level sensor XLEV, which determines level of molten metal. The advantages include fact that this sensor measures actual level of steel and full digital signal processing.

The steel casting speed will be measured using optical metal casting speed sensor – ProSpeed LSV-2100. The advantages include: precise laser measurement; non-contact measurement method; no need for recalibration; easy integration into processes with long distances of up to 3 m.

Information about position of lock is generated by linear displacement sensor mounted on hydraulic cylinder rod of locking mechanism. To measure position of stopper, linear encoder from LTR series is used, designed for short movements and equipped with return spring. An important feature of these sensors is presence of return spring.

The integration of above sensors and measuring devices into single automated control system requires use of specialized software capable of efficiently processing and analyzing data from various sources. To solve this problem, we chose Genie software package, which provides

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comprehensive support for a wide range of industrial automation hardware. The input/output drivers included in Genie package provide support for all industrial automation hardware, including data acquisition and control modules, IBM PC-compatible MIC2000 modular co-controller, remote data acquisition and control devices, and CAN industrial bus devices with DeviceNet protocol. The data center is set of dynamic linking libraries.

Consider technical means of controlling casting parameters.

Based on analysis of parametric model (1) and taking into account parameters of metal products formation, algorithm for automated system was developed, which is shown in Fig. 1.

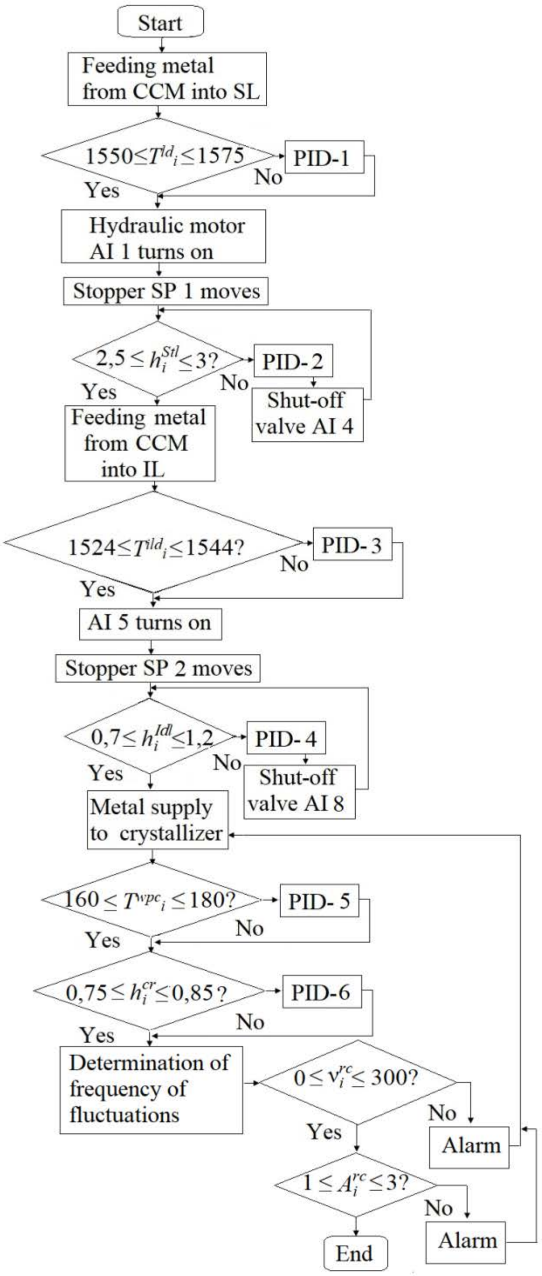

Figure 1 – Algorithm of control system operation

Stage 1: The automated system begins its operation by feeding metal (raw materials) from CCM into steel ladle.

Stage 2. Next, temperature of raw material in steel ladle is checked, if conditions are met, then hydraulic motor AI 1 is turned on, which pushes stopper in steel ladle AI 2. If conditions are not met, then control by PID 1 is required.

Stage 3. After that, level of raw materials in steel ladle is checked, if conditions are not met, then it is necessary to control AI 4 shut-off valve using PID 2. If conditions are met, then raw material enters industrial ladle.

Stage 4. Next, temperature of raw material in mill is checked, if conditions are met, then hydraulic motor AI 3 is switched on, which pushes stopper in mill SP 2. If conditions are not met, then control by PID 3 is required.

Stage 5. After that, level of raw materials in mill is checked, if conditions are not met, then it is necessary to control shut-off valve AI 8 with help of PID 4. If conditions are met, raw material enters crystallizer.

Stage 6. The algorithm is repeated, as in case of steel ladle or industrial ladle.

Stage 7. Determination of crystallizer vibrations frequency.

Stage 8. Checking conditions for vibration amplitude of crystallizer. If condition is met, then algorithm is completed, and if not, then error message (signal to indicator) is generated and algorithm returns to stage 7.

The developed algorithm is the result of formalizing a complex production process, which demonstrates the effectiveness of applying computer science methods (algorithm theory, system analysis, etc.) to model real systems.

The algorithm is built on basis of clear logical structure using conditional operators and loops, which is classical approach in algorithm theory and programming.

The algorithm implements principles of automatic control theory, in particular, use of PID controllers, which demonstrates integration of informatics methods and control theory.

Although this algorithm does not have explicit modular structure in classical sense, it has certain structuredness with successive processing and control stages, which reflects systematic approach to managing complex production process. Each stage of algorithm includes checking conditions and appropriate actions, which ensures flexibility and adaptability of control system to changes in process parameters.

4 EXPERIMENTS

Modern automated control systems are critical for industrial enterprises, as they help to increase efficiency, provide data processing for making informed decisions, and report system problems. This helps to reduce downtime and avoid shortages of both finished products and billets.

SCADA systems are backbone of many modern industries. The Genie system was chosen for development, which is one of SCADA packages.

The Genie system has module-oriented open architecture.

Development of system is reduced to user placing functional blocks in task window and establishing links

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between them, which are determined by data processing algorithm.

The openness of architecture ensures easy integration of Genie with other applications to share data during execution of strategies. Genie was chosen for this work because of its ease of use.

Based on developed algorithm, we created project that will include 2 modules:

1) Strategy, which consists of mnemonic scheme developed in «Task Editor».

2) The interface of automated system – on-screen form that is developed in «Form Editor». Connections between blocks of «Task Editor» and display elements of «Form Editor» are invisible – links.

A mnemonic scheme consisting of blocks and links between them has been created.

Task or TASK 1 – set of functional blocks displayed in Task Editor window.

TASK 1 is Task 1 window in «Task Editor», where mnemonic scheme is developed (Fig. 2).

AI units are connected to sensors that read values of measured parameters.

The AI block is designed to receive information from devices with analog signal input subsystem and transmit these signals to other blocks and display elements (Fig. 3).

Tag «Field» – name of tag in Genie system. The «Description» field is field for entering description of device (value in field is left by default). The «Device» field is used to select device to which this unit will be connected. The type of such device will be displayed in «Module» field of dialog box. The «Input Range» field is range of input signal. The «Expansion Channel» field is switch/amplifier of analog signals.

After selecting analog input device or module, set parameters of «From Channel» and «To Channel» channels (list of polled channels), from which information will be sent to analog input unit.

Some AI units are connected to ONF units via Conductor unit. It is AI 1 that receives signal from hydraulic motor.

The «Conductor» is used to establish visible connections between icons of functional blocks of task.

In Fig. 4 «ONF» block. The «ONF» block is designed to implement simplest two-position control algorithm and has input that receives feedback signal from control object and discrete output whose logical state depends on current value at input, setpoint and values of ON and OFF thresholds.

«Delta High» and «Delta Low» field – on/off threshold.

«Delta High» field – controller insensitivity zone when generating output signal that includes control object. The upper control limit is determined by summing exclusion threshold and setpoint value.

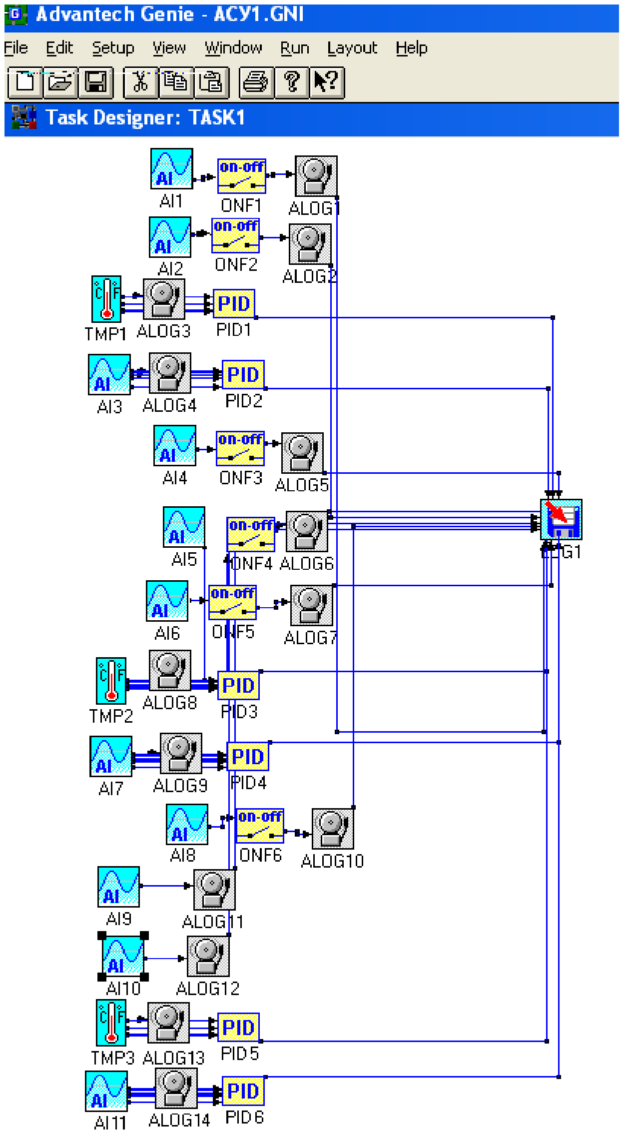

Figure 2 – Developed mnemonic scheme

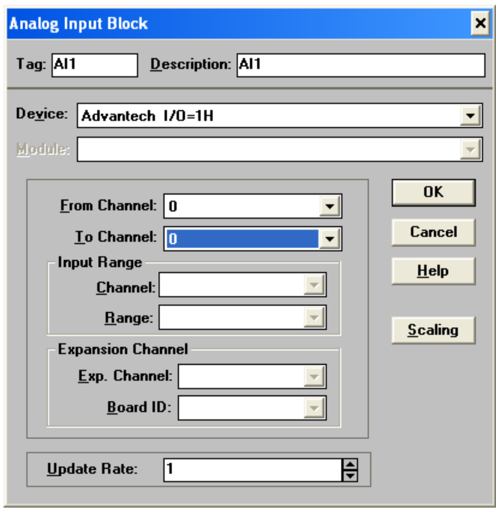

Figure 3 – Block configuration window «Analog Input Block»

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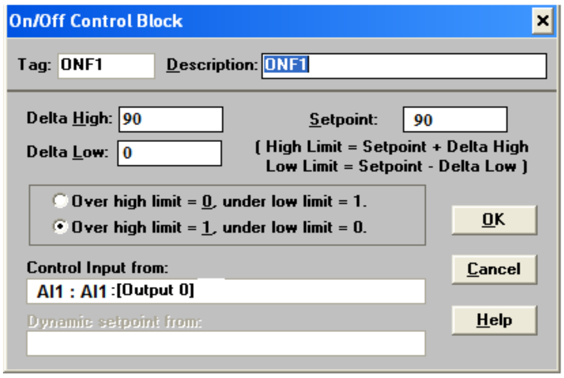

Figure 4 – Block configuration window «On/Off Control Block»

For example, «Engine» element can work in following modes: ON ($0 \to 90^\circ$) and off ($90^\circ \to 0^\circ$), then let rate be 90.

The «Setpoint» field contains value against which feedback signal at input of block is compared. The setpoint can be fixed or dynamically changed by signal from another functional block of strategy.

Field «Control Input from» – control input from output of channel 0.

Selected «Over high limit = 1, under low limit = 0» because if signal value is above upper limit, we assign value of 1 (motor is ON), and if it is below lower limit, 0 (motor is OFF).

Some «ONF» units are connected to «ALOG» (designed to store in archive information about recorded alarm events associated with signal received at input of alarm archive unit. The unit has input and output).

A description of mnemonic scheme elements connection to devices is given in Table 2.

Table 2 – Description of mnemonic elements connection

Element	Description
AI 1	Receives signal from hydraulic motor.
AI 2	Receives signal from LTR series position sensor, which detects position of stop № 1.
TMP 1	Receives signal from CEM DT, which measures temperature in steel ladle.
AI 3	Receives signal from XLEV sensor to measure level of raw materials (metal) in steel ladle.
AI 4	Receives signal from position sensor that controls shut-off valve №1.
AI 5	It receives signal from hydraulic motor, which sends signal to make stopper № 2 move.
AI 6	Receives signal from LTR series position sensor that controls position of locking mechanism №2.
TMP 2	Receives signal from CEM DT sensor, which records temperature in industrial ladle.
AI 7	Receives signal from sensor for measuring level of raw materials (metal) in IL – XLEV sensor.
AI 8	Receives signal from position sensor that controls shut-off valve № 2.
AI 9	It receives signal from sensor that measures vibrations frequency of crystallizer – digital frequency meter.
AI 10	Receives signal from sensor, measures amplitude of crystallizer vibrations – sensor 640B01.
TMP 3	Receives signal from CEM DT sensor that records temperature in crystallizer.
AI 11	Receives signal from sensor for measuring level of raw materials (metal) in crystallizer – XLEV sensor.

Blocks «TMP» 1 – 3 is connected to «ALOG» for temperature measurement.

Fig. 5 shows example of «ALOG» block configuration window.

Field «Alarm Settings» – values of alarm parameters. The values of signals at unit input fall into following ranges:
1 – above upper limit value High-High;
2 – maximum High value;
3 – below lower limit value Low-Low;
4 – minimum value Low.

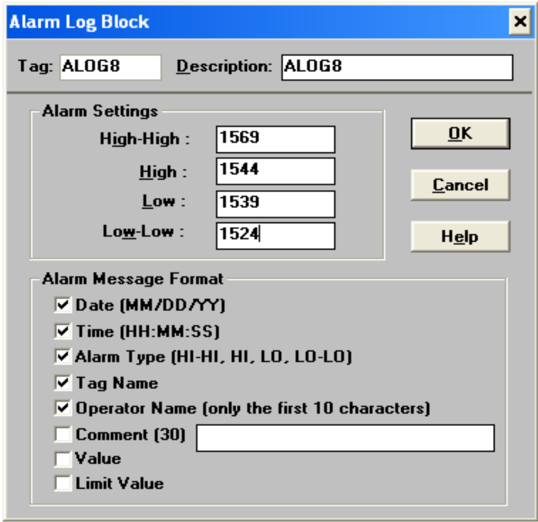

Figure 5 – Block configuration window «Alarm Log Block»

5 RESULTS

Each strategy has its own screen form – interface that is developed in «Forms Editor». The window of developed system interface consists of two displays, which are shown in Fig. 6, a, b.

As result, there are two developed interfaces: Display 1 – main and Display 2 – auxiliary for monitoring parameters of crystallizer: frequency and amplitude of vibrations.

The interface of automated system in Fig. 6 consists of elements:

– «Text string» – display has no means of communication with functional blocks and other elements of strategy display/control and is intended to display static character string on monitor screen, which is determined at stage of strategy development;

– «Display indicator» is single indicator used to display state of logical output associated with it in strategy functional block;

– «Text output field by condition» – for visualization of process in real time, provides ability to receive and transmit information;

– «Incremental regulator» – to control, in this case, temperature levels in steel casting and industrial ladles, crystallizer;

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– «Linear indicator» is used to graphically display value of parameter supplied from connected functional block of strategy;

– «Digital indicator» is used to display parameter value at output of connected functional block of strategy, as well as to display text strings coming from output of user procedure block or block of «Basic script» during strategy execution;

– «Analog regulator», which is used to control levels of raw materials;

– «Command Button (Menu Button)» is intended for creating buttons in window of display form that allow you to control process of strategy execution;

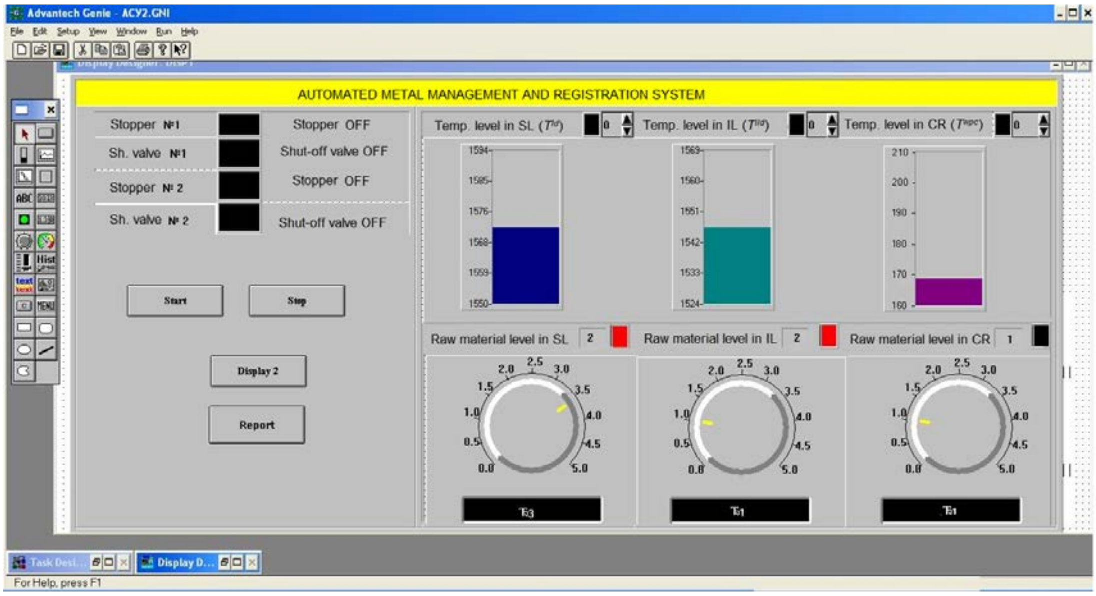
– display element «Arrow indicator» – presentation of information from associated functional block on graphical analog arrow indicator.

Thus, all elements can be classified as display and control elements.

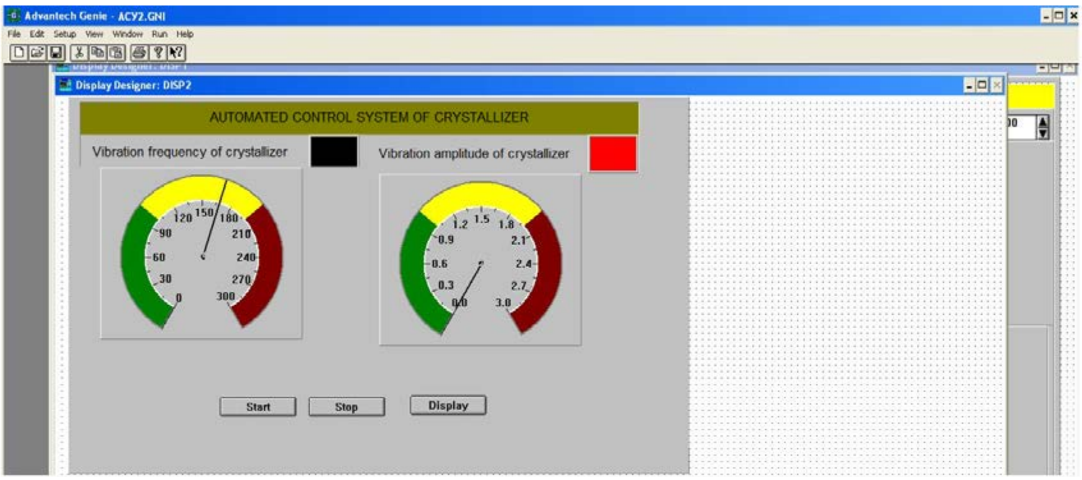
A daily report was created to record level of raw materials. Daily reports are designed to implement daily system summaries.

Fig. 7, a, b shows windows for creating report, namely. Fig. 7, a – selecting date and version of report for printing. Fig. 7, b – process of creating report configuration.

A report with particular identification number can be activated (Enabled) or blocked (Disabled). If report is blocked, it will not be printed during strategy execution.



a



b

Figure 6 – Interface to automated system for managing and registering raw materials:
a) Display 1; b) Display 2

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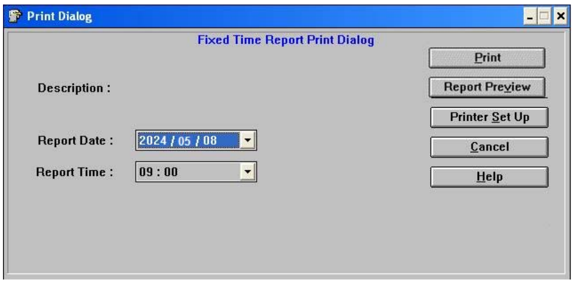

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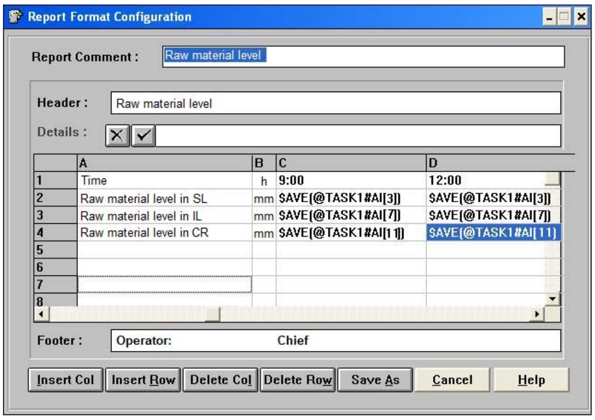

b

Figure 7 – Customization windows in process of creating report

The report is printed at time set in editing fields with numbers from 1 to 24 in «Report Time» parameter group.

As result, when formulating context of this work, its main goal was determined – development of automated metal management and registration system to improve quality of metal products. As result of this work, this goal has been achieved because:

– current state of production in field of continuous casting is analyzed;

– features of MP molding stages of are analyzed;

– parametric model of CC that is complex is proposed;

– key parameters of metal product molding are selected and described;

– technical means for controlling casting parameters were selected;

– algorithm for operation of proposed automated system was developed;

– developed mnemonic scheme in «Task Editor»;

– description of mnemonic elements connection to mnemonic elements is given;

– two interfaces have been developed: Display 1 – main and Display 2;

– efficiency and reliability of developed system was compared with existing commercial solutions.

The developed mathematical models and algorithm have been successfully tested on example of continuous metal casting controlling process. However, proposed approach is universal in nature and can be applied to wide class of complex production processes in various industries.

6 DISCUSSION

The developed automated system for controlling and registering metal in continuous casting is represented by complex interface consisting of two displays with elements for displaying and controlling key parameters of casting mould.

A comprehensive visual interface provides clarity and ease of navigation for operator, which is critical when working with automated control systems.

To compare development with similar systems, we selected programs used to control continuous casting machine.

The software for controlling continuous casting machine is in closed access, but there are modules for modeling metal casting.

The Electrical and Automation Systems for Continuous Casting Plants from Ingeteam [16] was chosen for consideration. This system also has its own modular automation solutions:

– MLC – raw material level monitoring;

– MWC – mold width monitoring;

– Gap monitoring – monitoring temperature of mold, predicting gaps;

– TLC – steel level control in metal casting machines;

– weight control in ladle tower, pouring trolley, product;

– measuring temperature and oxygen content in liquid steel;

– optimized billet tracking to marking devices.

Another analog is ABAX TubeStar with sets of modular automation solutions [17]:

– SprayStar Secondary and Cooling Automation provide optimal thermal profile of billet, taking into account variable casting conditions such as speed, steel composition, and overheating;

– MouldStar is module for controlling level of raw materials;

– Process Star for monitoring and collecting process data, billet quality forecasting, melt and billet reports, and equipment life tracking;

– TubeStar for monitoring condition and history of all crystallizer tubes, which is critical parameter of casting process.

Thus, system allows monitoring and displaying all necessary information for each casting mold used.

ABAX MouldStar is available as stand-alone package and can be implemented on any filling machine.

In such systems, user enters input data required to monitor molding process step by step, which can be displayed in reports.

To conduct experiment of automated control system, input data from Table 3 were used to monitor metal level during molding.

We will evaluate efficiency and reliability of developed system in comparison with existing commercial solutions.

The experiment consists of two stages, which will be compared:

1) data entry;

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2) monitoring process of forming slab product.

Therefore, it is necessary to test system's ability to correctly process input data and monitor process of forming slab product.

The main comparison criterion is number of module malfunctions detected within three days.

Fig. 8 shows results in form of diagram.

Table 3 – Input data of experimental study

Characteristics	Filling speed, m/min	Vibration frequency, rpm	Vibration amplitude, mm	Metal level in SL, mm	Metal level in IL, mm
Meaning	1	162	2	2,5	0,7
	2	163	2	2,5	0,8
	3	164	3	2,5	0,8
	4	165	3	2,7	0,9
	5	165	4	2,7	0,9
	6	165	4	2,8	1,0
	7	166	4	2,9	1,0
	8	164	5	3,0	1,2
	9	166	5	3,0	1,3
	10	166	5	3,1	1,4

In Fig. 8: – MouldStar from ABAX, – Electrical and Automation Systems for Continuous Casting Plants from Ingeteam – developed system.

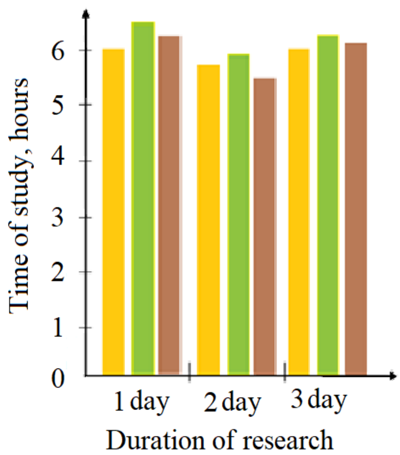

Figure 8 – Diagram comparing average operating time of developed system and analogs

As result, selected systems are stand-alone modules specialized for narrow range and designed for specific type of continuous casting machine. It was found that over three days of operation, these modules demonstrated greater reliability compared to ABAX MouldStar and Ingeteam's Electrical and Automation Systems for Continuous Casting Plants.

The system's ability to work with real data and production conditions was tested.

The developed system allows user to enter data to monitor crystallizer step by step, ensuring high stability of meniscus level, safe operation and easy operation.

The low installation and maintenance costs make this system advantageous choice for controlling continuous casting plant. Experimental results confirm advantages of this development over ABAX's MouldStar and Ingeteam's Electrical and Au-tomation Systems for Continuous Casting Plants in controlled steel casting.

CONCLUSIONS

The urgent problem of developing automated system for controlling and registering metal in continuous casting has been solved.

The scientific novelty of results obtained is that is that for first time, comprehensive parametric model of continuous metal casting process has been developed based on methods of set theory and system analysis. This model is universal tool for formalizing and optimizing processes in various industries. The proposed model integrates not only product molding modes, but also takes into account specific properties of source material and design features of the casting equipment. This model is presented as set of interrelated parameters, with each element reflecting specific aspect of casting process. The parametric model differs from existing ones in its comprehensiveness and integration of various aspects of casting process. It provides basis for developing more accurate and efficient control systems, which can potentially lead to significant improvements in product quality and production efficiency.

The practical value of results obtained is to develop automated control system that implements control of key parameters in continuous casting with ability to collect, process and record data in real time, as well as to implement control of key parameters in continuous casting. The experiments conducted using real production data demonstrate effectiveness of developed algorithm, which is result of formalizing complex production process, demonstrating effectiveness of computer science methods (algorithm theory, system analysis, etc.) for modeling real systems. Based on results of experiment to evaluate efficiency and reliability of developed system, it is possible to recommend proposed system for use in practice.

The results obtained make significant contribution to development of information systems for managing and monitoring complex production processes. They ensure improved product quality and optimization of production processes through introduction of user-friendly system for visualizing and controlling key parameters. The developed system, which includes two informative screens (Display 1 and 2), allows operators to more effectively monitor and control casting process, resulting in reduction in defects and increase in overall production efficiency. These achievements create solid foundation for further technological improvements in steel industry.

Prospects for further research are to investigate new methods of secondary cooling to improve surface quality and internal structure of workpieces. In addition, there is area for improving non-destructive testing methods to detect defects in real time during casting process. The developed automated system creates basis for further im-

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provement of management technologies in steel industry, in particular, for introduction of machine learning and predictive analytics methods to predict product quality and optimize production parameters.

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РОЗРОБКА АВТОМАТИЗОВАНОЇ СИСТЕМИ УПРАВЛІННЯ ТА РЕЄСТРАЦІЇ МЕТАЛУ ПРИ БЕЗПЕРЕРВНОМУ ЛИТТІ

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АНОТАЦІЯ

Актуальність. Сучасні промислові підприємства стикаються з викликами, які вимагають впровадження новітніх технологій для підвищення ефективності та конкурентоспроможності. У металургії одним із ключових етапів є безперервне лиття, де від точності та оперативності управління процесом залежить якість виробів та економічні показники підприємства. Вироби, отримані за технологією безперервного лиття, знаходять широке застосування у різних галузях промисловості завдяки своїм високим механічним властивостям, однорідності структури та економічній ефективності.

Розробка автоматизованої системи управління та реєстрації металу стає не лише актуальною, але й необхідною для забезпечення стабільного та ефективного виробництва.

Проблема підвищення якості виробів з металу завжди була однією з найважливіших завдань металургійної галузі. Недосконалість технологічних процесів, людський фактор, а також збої в роботі обладнання можуть призводити до виникнення дефектів у готових металевих виробах. Це, у свою чергу, впливає на кінцеві характеристики виробів, їх довговічність та надійність.

На сьогоднішній день у наявних джерелах ця проблема ще не знайшла повного вирішення. Тому необхідно здійснити постановку задачі та розробити алгоритм роботи автоматизованої системи управління та реєстрації металу при безперервному литті.

Мета. Метою дослідження є розробка автоматизованої системи управління та реєстрації металу для підвищення якості металевих виробів.

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Метод. Для щоб досягти поставленої мети, була запропонована комплексна параметрична модель, яка формалізована на базі теорії множин. Модель враховує ключові параметри процесу безперервного лиття: матеріал, конструкційні особливості кристалізатору, режими розливання, рівень металу в кристалізаторі та положення стопора промковшу.

Результати. Здійснена постановка задачі та визначені ключові параметри, які враховані в алгоритмі роботи системи, а це дало можливість розробити систему управління установкою безперервного лиття для вирішення задачі підвищення якості отриманої заготовки.

Висновки. Для підвищення якості отриманих виробів з металу та стабільності процесу лиття створено параметричну модель, яка є комплексною, дозволяє оптимізувати ключові параметри та забезпечує точність керування процесом за рахунок того, що інтегрує не лише режими формування виробів, але й враховує специфічні властивості вихідного матеріалу (хімічний склад марки матеріалу і т.п.) та конструктивні особливості установки для лиття. Розроблено алгоритм роботи автоматизованої системи управління, який враховує взаємозв'язки між визначеними ключовими параметрами та забезпечує оптимальне керування процесом лиття. На базі запропонованої параметричної моделі та алгоритму створено автоматизовану систему управління та реєстрації металу. Фокус роботи направлений на якість та ефективність управління та реєстрації металу при безперервному литті, що базується на сучасних методах інформатики та обчислювальної техніки. Проведено комплексне експериментальне порівняння розробленої системи з комерційними аналогами в умовах реального виробництва, що дозволило об'єктивно оцінити її ефективність та надійність.

КЛЮЧОВІ СЛОВА: автоматизація, система, параметрична модель, управляння, реєстрація, метал.

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INFORMATION SYSTEM OF STREET LIGHTING CONTROL IN A SMART CITY

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ABSTRACT

Context. In the context of the rapid development of technologies and the implementation of the concept of smart cities, smart lighting becomes a key element of a sustainable and efficient urban environment. The research covers the analysis of aspects of the use of sensors, intelligent lighting control systems with the help of modern information technologies, in particular such as the Internet of Things. The use of such technologies makes it possible to automate the regulation of lighting intensity depending on external conditions, the movement of people or the time of a day. This contributes to the efficient use of electricity and the reduction of emissions into the atmosphere.

Objective. The purpose of the paper is to analyze the procedures for creating an information system as a tool for monitoring and evaluating the level of illumination in a smart city with the aim of improving energy efficiency, safety, comfort and effective lighting management. The implementation of a smart lighting system for Lviv will help improve energy efficiency and community safety.

Method. A content analysis of scientific publications was carried out, in which the results of research on the creation of street lighting monitoring systems in real urban environments were presented. The collection and analysis of data on street lighting in the city, such as energy consumption, illumination level, lamp operation schedules, and others, was carried out. Machine learning methods were used to analyze data and predict lighting needs. Using the UML methodology, the conceptual model of the street lighting monitoring information system was developed based on the identified needs and requirements.

Results. The role of data processing technologies in creating effective lighting management strategies for optimal use of resources and meeting the needs of citizens is highlighted. The study draws attention to the challenges and opportunities of implementing smart lighting in cities, maximizing the positive impact of smart lighting on modern urban environments. The peculiarities of the development and use of an information system for controlling street lighting in a smart city are analyzed. The potential advantages and limitations of using the developed system are determined.

Conclusions. The project on the creation of an information system designed to provide an energy-efficient lighting system in a smart city will contribute to increasing security, particularly, ensuring the safety of the community through integration with security systems, reducing energy consumption, through minimizing the electricity usage in periods when the need for lighting is not necessary.

It has been determined that to implement an information system for remote monitoring and lighting control in a smart city, it is advisable to consider the possibility of using a complex lighting control system. Calculations were made on the example of Lviv for the city's lighting needs. The use of motion sensors to determine the need to turn on lighting was analyzed. A conceptual model of the information system was developed using the object-oriented methodology of the UML notation. The main functionality of the information system is defined.

KEYWORDS: information system, lighting system, smart city, remote monitoring, forecasting.

ABBREVIATIONS

IoT is an internet of things;
UML is an Unified Modeling Language;
RNN is a recurrent neural networks;
LSTM is a Long Short-Term Memory;
MQTT is a Message Queue Telemetry Transport.

NOMENCLATURE

D is a distance between measurement points;

S is a distance between lamps in meters;

N is a number of measurement points in the longitudinal direction;

l is a shading coefficient;

E_{zb} is an illumination level with trees;

E_{bb} is an illumination level without trees;

W_r is a width of the road or the considered section;

n is a number of measurement points in the transverse direction;

L is a total number of lamps;

k is a number of lamps at the intersection;

P is a number of intersections;

m is a number of lamps on the street;

n is a number of measurement points in the transverse direction;

V is a number of streets;

E is a total consumed energy;

P is a lamp power;

T is a working time per day;

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$D(t)$ is a lighting dynamics;

$I(t)$ is an intensity of lighting on the street;

k is a positive attenuation coefficient of the lighting intensity;

a is a positive influence coefficient;

$R(t)$ is a traffic level on the street;

x_t is an input vector;

h_{t-1} is a hidden state in the previous step;

f_t is a forgetting vector, which determines which information from the previous state of the cell (h_{t-1}) should be "forgotten";

i_t, o_t are input and output vectors;

c_t is a state of the cell;

W_m are weight matrices;

b_l are displacement vectors;

σ is a sigmoid function;

$\tanh$ is a hyperbolic tangent.

INTRODUCTION

A smart city is a concept that is based on the use of information and communication technologies to increase work efficiency, exchange information with the public and ensure better quality of public services and citizens' well-being. The main goal of a smart city is to optimize city functions and promote economic growth, as well as improve the quality of life of citizens with the help of smart technologies and data analysis, in the field of street lighting.

Street lighting is the main part of city infrastructures. In addition to the main function of controlling and regulating street lighting, smart lighting can have other important functions that contribute to the functioning of a smart city. The development of intelligent street lighting systems is one of the topics that interests many researchers around the world. Therefore, the creation of an information system for quality control of street lighting in a smart city is an important and relevant topic.

The **purpose** of the paper is to analyze the procedures for creating an information system as a tool for monitoring and evaluating the level of illumination in a smart city with the aim of improving energy efficiency, safety, comfort, and effective lighting management. The implementation of a smart lighting system for the city of Lviv will help improve energy efficiency and community safety.

The object of research is the street lighting system of smart cities.

The subject of research is methods and means of building a smart lighting system in a smart city.

The scientific novelty of the obtained results lies in the development of a unique system that is a part of a local, wireless, decentralized network for collecting data from sensors on lampposts, processing them to ensure energy efficiency and safety of public lighting, which, unlike existing solutions, provides an opportunity to take into account the features of the urban infrastructure of Lviv and effectively manage the lighting system in the city.

1 PROBLEM STATEMENT

In the context of a smart city, the street lighting management information system plays a crucial role in ensuring the efficiency, safety, and comfort of residents' lives. Formalizing this task involves determining the optimal distribution of lighting resources, taking into account various factors such as energy efficiency, safety, comfort, and economic feasibility.

Input Variables: S; N; E_{zb}; E_{bb}; W_r; n; k; P; m; V; P; T; $I(t)$; k; a; $R(t)$.

Desired outcomes (output variables): D; l; L; E; $D(t)$.

D depends on S and N. For $S \le 30m$ it is $N = 10$, and for $S > 30m$, it is the smallest integer that gives $D \le 3m$.

l depends on E_{zb} and E_{bb}. In turn, D depends on W_r and n. n which is equal to 3 or more and is an integer, which gives $d \le 1.5m$.

L depends on k, P, m, l and V. And E depends on L, P and T.

$D(t)$ depends on k, $I(t)$, a and $R(t)$.

Mathematical modeling of these parameters will allow for the development of optimal solutions for street lighting management in a smart city, ensuring efficient resource utilization and meeting the needs of the population.

2 REVIEW OF THE LITERATURE

Public lighting infrastructure, according to researchers, offers not only smart lighting, but also several other functions and benefits for cities. Using lampposts to integrate sensors from other smart city systems, such as air quality monitoring, Wi-Fi provision, video surveillance for public safety and electric vehicle charging. Researchers believe that high-quality street lighting significantly increases the productivity of smart cities and the quality of life of its citizens. The use of innovative lighting systems is characteristic of smart cities in Europe, Asia, and North America, which have already created the concept of a smart city, many others are developing detailed plans and conducting analysis to reach this stage of development and in the context of the lighting system [1].

The authors of the paper [2] believe that the field of lighting management creates opportunities for the use of sensor technologies with information and communication technologies. This approach contributes to the efficient use of electricity for lighting the city and reducing its negative impact on the environment. Semiconductor light sources, in particular Light Emitting Diode, and LED

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technologies, such as organic LEDs or solid-state light sources, are used to implement the intelligent lighting system. Researchers believe that the development of new relations in this field is mainly focused on the creation of modern lighting control information systems that provide dynamism, controllability and interactivity, adaptability of control procedures. The use of intelligent solutions for lighting ensures automatic detection of failures and efficient use of energy.

Researchers [3] believe that in a smart city, when implementing intelligent lighting systems, it is advisable to combine lighting systems and communication channels with advanced intelligent functions. To ensure lighting control procedures, the authors proposed several IoT usage scenarios [4]. The authors believe that to build an ecosystem of a smart city, it is advisable to use individual systems and solutions taking into account the unique requirements of each city [5], while four conditional categories are distinguished such as citizens, mobility, government and environment [6]. And in order to increase the efficiency of lighting systems, it is necessary to conduct interdisciplinary research to solve many problems, in particular, the features of connecting components using a protocol with IoT support to ensure energy efficiency in a smart city [7].

According to the authors of the paper [1], street lighting is important for ensuring the comfort and safety of road traffic for its participants. At the same time, it is noted that a properly designed and properly executed installation of street lighting will contribute to the creation of safe traffic conditions for drivers, cyclists, and pedestrians in the dark season. In many countries, for economic reasons, the lighting of all streets and roads is not used when there is no traffic on them, but some places and areas are determined that must be lit constantly [8].

A smart lighting system is an automated intelligent lighting control system that involves the use of Internet of Things technologies, devices, and sensors for lighting public places, which are an important part of the urban environment. The use of an intelligent information system of smart lighting contributes to the general feeling of safety and comfort of pedestrian movement in the dark [9, 10]. Factors affecting the feeling of security in the dark time of the day include not only the concept of "illumination", but also other attributes, such as uniformity, light-color transmission, and color temperature of light [11].

Considerable research in the field of neural networks is conducted by Ukrainian scientists. So, there is an intensive search for an evolutionary approach for the structural synthesis of neural networks [12, 13, 14].

3 MATERIALS AND METHODS

A content analysis of scientific publications was carried out, in which the results of research on the creation of street lighting monitoring systems in real urban environments were presented. The collection and analysis of data on street lighting in the city, such as energy consumption, illumination level, lamp operation schedules, and others, was carried out. Machine learning methods were used to analyze data and predict lighting needs. Using the UML methodology, a conceptual model of the street lighting monitoring information system was developed based on the identified needs and requirements.

Using the method of recurrent neural networks (RNN) and Long Short-Term Memory (LSTM), modeling of temporal dependencies in time series was carried out, which made it possible to create a model for predicting street lighting needs.

The project development for the creation of innovative public lighting control systems was carried out by a virtual team consisting of territorially distributed members, among whom are highly co-specialized experts in various fields of knowledge. This approach made it possible to work in different time zones. It is undeniable that managing a virtual team required not only a review of the management strategy, but also ensuring effective interaction between team members, despite their physical distance and dispersion in time zones. The key factors for improving the productivity of members' work were determined to establish team interaction (Fig. 1).

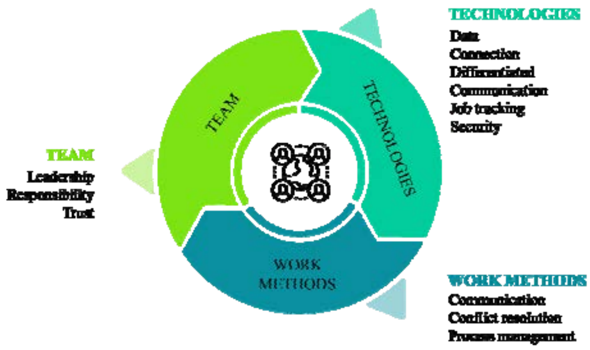

Figure 1 – The key factors to improve virtual team performance

The goals of the project are presented in Fig. 2.

The goals of the project (Fig. 2) in general can be presented as increasing the level of public lighting management, reducing maintenance costs, remote control of each lamp separately, the ability to change the brightness of the light stream depending on the length of a day and weather conditions, energy conservation, due to fluctuating lighting levels depending on traffic, increasing the city's security level, using Internet of Things technologies to improve the city's technological development, the ability to find the safest routes for city residents and guests.

Various algorithms for measuring illumination levels are used for the effective work of the information system, by receiving data from sensors and processing them in real time. Measurements are carried out horizontally on the road surface according to requirements. The location of the measurement points depends on the distance between the lamps and the width of the strip. Illumination measurement in the information system will be carried out on each investigated area, choosing two consecutive lamps in one row in the longitudinal direction, and in the transverse direction it is chosen the width of the area with

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the same illumination class, if the road, adjacent sidewalk or bicycle path have the same illumination class, they can be treated as one area during measurements. The measurement points must be evenly distributed within the measurement field.

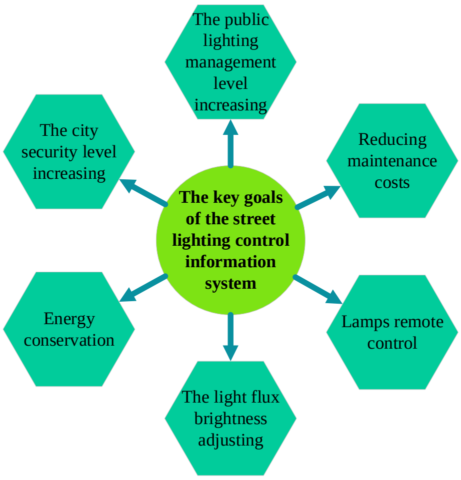

Figure 2 – The key goals of the street lighting control information system

The distance between measurement points (D in (m) in the longitudinal direction should be calculated using the formula 1:

$$D = \frac{S}{N}. \quad (1)$$

In the case of the presence of elements (trees, buildings) that shade certain areas, it is necessary to take this into account when calculating the illumination. It is supposed that there are trees between a light source (like a lamp) and the measurement points. It is advisable to determine how these trees affect the level of illumination at these points by means of computer simulation.

Using light modeling software, it is created a 3D model of our environment with trees and a light source. After that, it is set parameters such as the height and width of the trees, their location from the light source, the light intensity of the source, as well as the properties of the environment (for example, air transparency).

First, it is simulated the illumination at the measurement points without shading by trees. This gives us a baseline light level that will be used to compare with the light level after shading. Then trees are added to our model, and it is restimulated the illumination at the same measurement points. With the help of software, the level of illumination at each point is measured and compared with the base level without shading.

This will determine the shading coefficient. The shading coefficient can be defined as the ratio of the illumination level with trees to the illumination level without trees according to Formula 2:

$$l = \frac{E_{zb}}{E_{bb}}. \quad (2)$$

Therefore, it is obtained the shading coefficient, which reflects how much the trees affect the level of illumination at the measured points. This coefficient is used in the formula to determine the illumination according to your initial formula.

The distance between measurement points D in meters in the transverse direction should be calculated using the formula 3:

$$D = \frac{W_r}{n}. \quad (3)$$

The distance between points and edges of the surface under consideration should be $D/2$ in the longitudinal direction and $d/2$ in the transverse direction.

Territory of implementation of the information system is the city of Lviv and adjacent territories.

The system objects are streetlights and lamps, motion and lighting sensors, a central server for data collection and processing.

Functional capabilities are automated adjustment of lighting brightness, motion detection, adaptation of lighting to the needs of the city at certain hours and its zones, integration with other city systems.

One of the ways to adjust brightness in a smart lighting system can be through setting the optimal number of lighting control sensors. It will be calculated the number of sensors for the city of Lviv, using the following input data:

The area of the city is about 182 square kilometers.

The number of streets and intersections in Lviv is 500 streets and 1000 intersections.

The type of lighting involves the use of LED lamps, which are an energy-efficient and long-lasting option for street lighting.

Lighting intensity is regulated by lighting standards, which may vary depending on the type of streets. Main roads are expected to have a higher intensity of light compared to residential streets. Let's focus on the average lighting intensity of 20 lux.

The working hours of the lighting system will be 10 hours a day (for example, from 6:00 p.m. to 4:00 a.m.).

Sensors and switch-off conditions take into account the possibility of using motion sensors or other conditions to automatically switch off the light in places where there is no traffic.

It will be calculated the approximate number of LED lamps and the energy they will consume for lighting in Lviv. It is supposed that there are LED lamps at each intersection and along each street. Thus, the total number of lamps will be equal to the number of intersections and streets:

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$$L = kP + mV\ . \quad (4)$$

Taking into account the shading coefficient. The shading coefficient is considered as a multiplier that reduces the number of lamps depending on the level of shade caused by any objects or structures in the city. Thus, the modified formula for calculating the number of LED lamps, taking into account the shading coefficient, will be:

$$L = kP + mV \times l\ .$$

It is supposed that there are 4 lamps at each intersection, and lamps are installed every 20 meters on each street.

$$L = kP + mV = 1000 \times 4 lamps + 500 \times 1000 : 20\ .$$

Total number of lamps = 4000 + 25000 = 29000 lamps.

The energy calculation will depend on the power of each lamp and the time of their operation. It is assumed that each lamp has a power of 30 W.

$$E = L \times P \times T\ . \quad (5)$$

$$E = 29000 \times 30 \times 10 = 8700000 Wh = 8700 kWh\ .$$

The information system for monitoring the level of illumination in a smart city is designed to provide comprehensive and effective control of the level of illumination in the urban environment to improve energy efficiency, safety, and comfort of residents. The information system is designed to collect, process, and analyze data on the level of illumination on streets and other public places. The Internet of Things technology and protocols to ensure stable communication are used to implement data transmission in the smart lighting system.

The functional requirements for the lighting control information system in a smart city (Fig. 3) can be presented as follows:

1. Monitoring and data collection. The ability of the system is to measure and record the level of illumination in real time. The ability is to collect data from sensors that measure light levels on different streets and at different times of the day.

2. Dynamic adjustment of lighting. The ability is to automatically adjust the brightness of the lighting depending on the time of a day, weather conditions, the presence of pedestrians and traffic.

3. Energy saving. There is an implementation of energy saving algorithms and modes to optimize the use of electricity.

4. Emergency modes. There is an ability to switch to emergency lighting modes in case of accidents, poor visibility, or other unforeseen situations.

5. Analytics and reporting. Analytical tools are for determining optimal lighting parameters in different areas of the city and at different times of the day. Reports are available on electricity consumption, efficiency, and other parameters.

6. Integration with other systems. There is a possibility of integration with other smart city systems to coordinate lighting with other infrastructural systems.

7. Control of lighting zones. The ability is to group street lighting into different zones and independently control each zone.

8. Remote control. There is a possibility of remote monitoring and control of the system through a web interface or a mobile application.

9. Automated scripts. It is to set up automated scenarios depending on the city's needs and conditions.

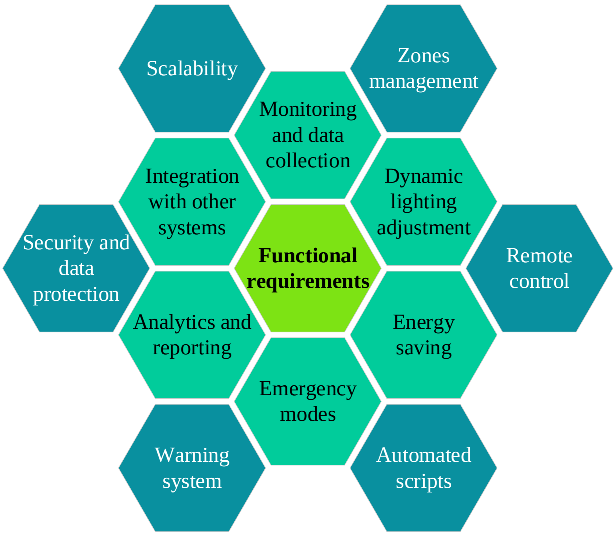

Figure 3 – Functional requirements for the lighting control information system

10. Warning system. There is notification and warning system in case of problems or accidents.

11. Security and data protection. There are mechanisms for protection against unauthorized access and ensuring data confidentiality.

12. Scalability. There is a possibility of expanding the system by increasing the number of sensors and lighting points.

These functional requirements serve as the basis for the further development of a detailed technical task for a system for evaluating the level of illumination in a smart city.

Having decided on the list of functional requirements for the lighting control information system in a smart city, it is created a use cases diagram (Fig. 4). The diagram shows the actor as a user who uses the interface produced by the information system.

After choosing a location, you can evaluate the level of illumination, analyze the results, and use scenarios to control lighting devices. Scenarios make it possible to quickly respond to changes in lighting and to perform specified sequences of actions when pre-defined conditions are met.

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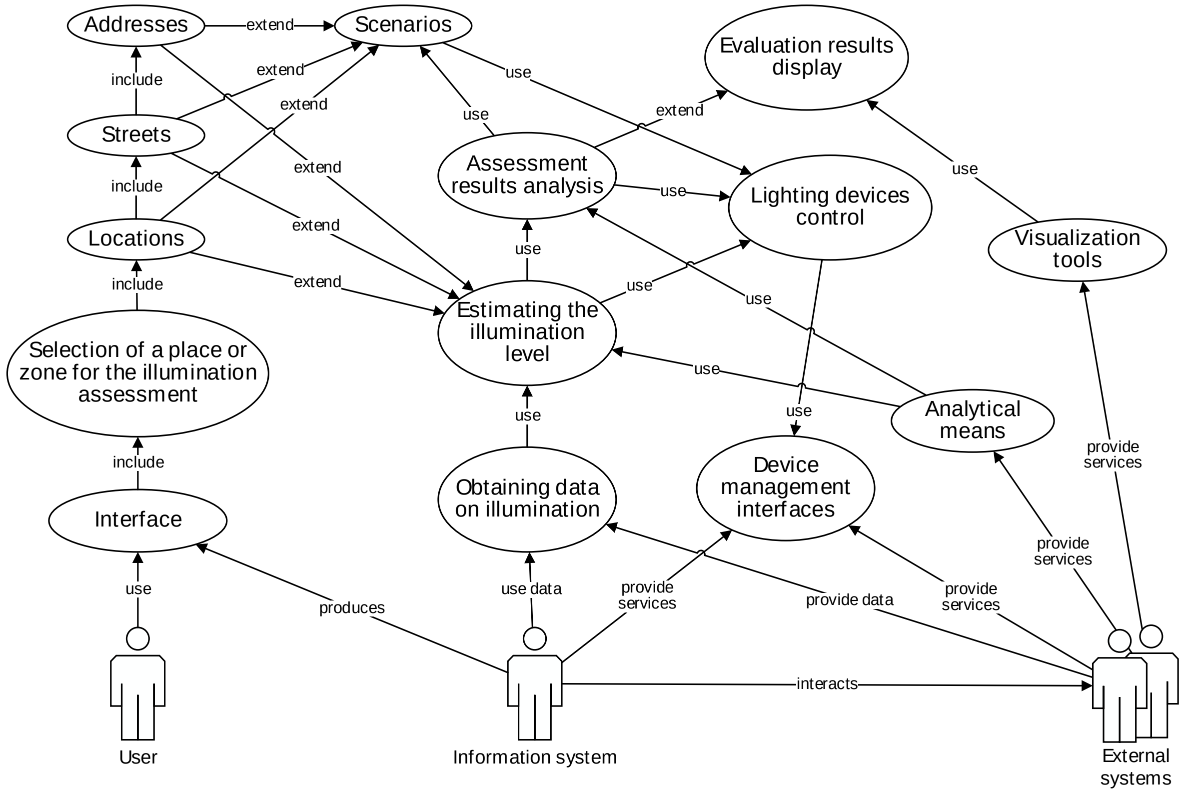

Figure 4 – Functional requirements for the lighting control information system

In this diagram, the Information System is highlighted as a separate actor because it consumes lighting data, produces the user interface, and provides interfaces to lighting control services.

Actors of External systems provide additional interfaces for lighting control services, analytical and visualization tools.

One of the key advantages of the information system is an ability to quickly respond to changes in environmental conditions and adjust lighting, accordingly, thereby ensuring the safety and comfort of citizens.

To achieve the goal of the project, it is envisaged to create and implement an integrated information system for assessing the quality of lighting in a smart city.

The information system for assessing the quality of lighting in a smart city will function with the aim of improving the quality of life of residents and optimizing energy saving management in the city of Lviv. The pro1ject aims to use advanced technologies to create an effective, safe, energy-efficient, and intelligent lighting system that considers the needs of different areas of the city and ensures their integration into the general infrastructure of a smart city.

The information system facilitates the possibility of improving the street lighting system, including different modes of operation, sensors, automation capabilities and other functions. The entire system of interconnected lights allows you to quickly identify areas with faulty lights, which will be immediately displayed in the information system.

The UML Activity diagram for the main flow for an ordinary user is presented in Fig. 5. Launching the system determines the beginning of the assessment of the illumination level and provides that:

– Reading light data involves obtaining relevant data from sensors or other sources.

– Determining the level of illumination includes processing the received data to determine the level of illumination.

– The illumination level is evaluated according to certain criteria.

– Light condition detection determines if the light level is acceptable or if intervention is required.

– Interaction with other systems of a smart city involves the possibility of communication with other subsystems to coordinate actions.

– Starting automatic lighting control modes involves activating automatic modes according to lighting requirements.

– Completing the assessment and saving the results describes completing the assessment process and saving the results for later use.

This diagram illustrates the sequence of steps that the system takes when estimating the illumination level in a smart city.

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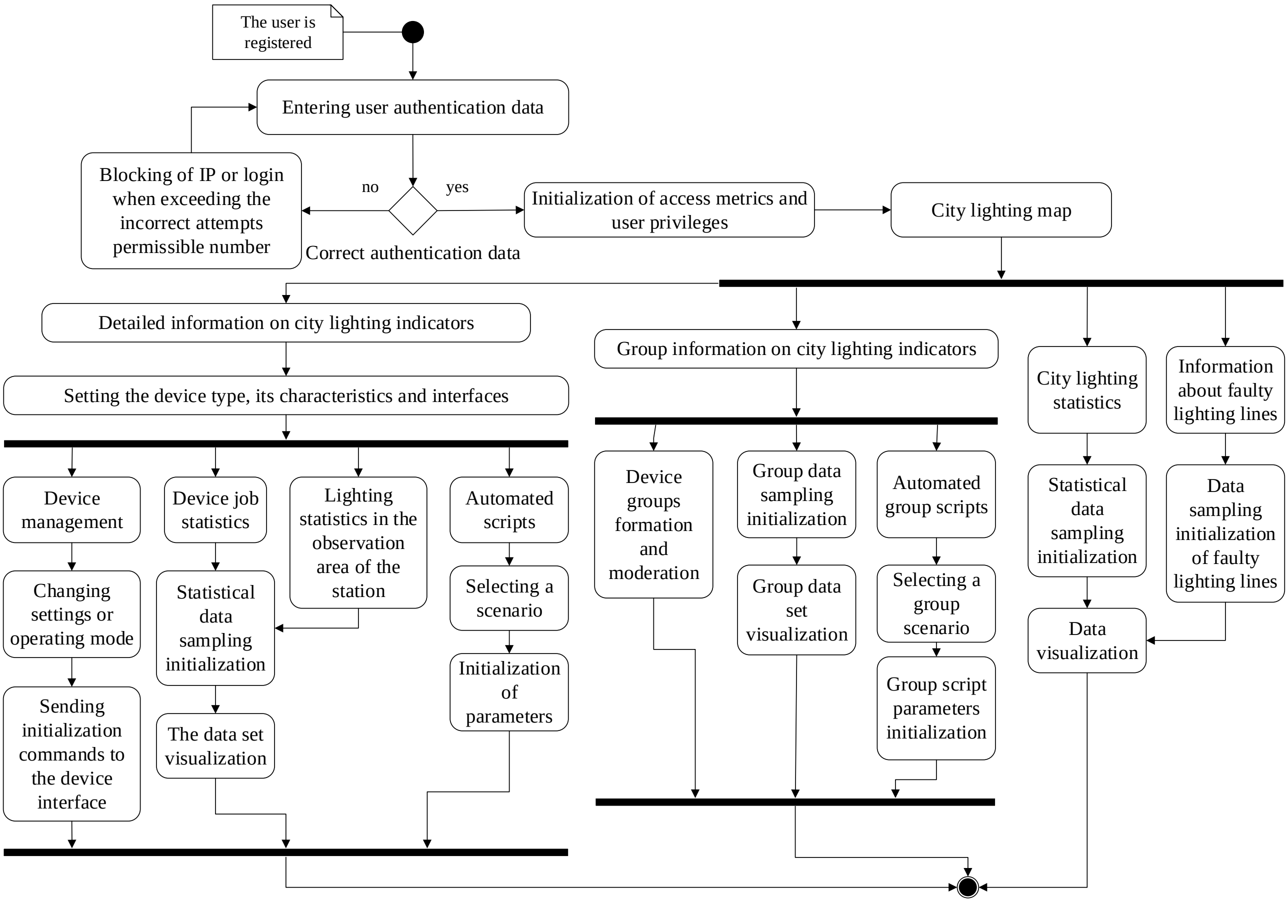

Figure 5 – UML activity diagram of the main sub-processes and actions of the street lighting control information system

To implement an information system for remote monitoring and control of lighting in a smart city, it is advisable to consider the possibility of using a complex lighting control system.

The information system of remote monitoring and control of lighting in a smart city provides for the presence of many elements and several functions.

Sensors and actuators. It is expedient installation of lighting, temperature, movement and other sensors on illuminated objects and areas of the city. Actuators for remote lighting control are used to change the state of the lighting system from a remote location. The information system provides the possibility of turning on and off the lighting remotely. The command to turn on or off is transmitted through the network from the central system to the actuators. The system will allow you to remotely adjust the brightness of the lighting.

To control actuators in smart lighting systems, it is advisable to use general algorithms, such as:

Remote on/off. The algorithm will provide the possibility of turning on and off the lighting remotely. The command to turn on or off is transmitted through the network from the central system to the actuators.

Brightness adjustment. The system will allow you to remotely adjust the brightness of the lighting. The algorithm can consider the parameters specified by the user or automatically react to changes in lighting conditions (for example, a change in the time of a day). To monitor the level of illumination, light sensors are installed that measure the level of illumination in certain areas of the city.

Definition of user parameters. The user can set their own parameters, such as the desired level of illumination, the schedule of changes in brightness during the day, automatic adjustment of illumination. The system automatically adjusts the brightness of the lighting depending on the received sensor measurements and user parameters. If the level of illumination deviates from the one set by the user, the system issues a command to the actuators to change the brightness.

The system will have built-in scripts that respond to certain conditions. For example, there is turning on a bright light in the morning or when natural light is reduced. The user can remotely control the brightness of the lighting through a mobile application or the web interface of the system (Fig. 6). The system can store data about the mode selected by the user and the reaction to various conditions. This data can be used to improve algorithms and train the system. These values may vary depending on specific parameters such as lamp efficiency, light intensity, and other factors. The possibility of using energy saving and optimization technologies to reduce energy consumption is also considered. To adjust the brightness

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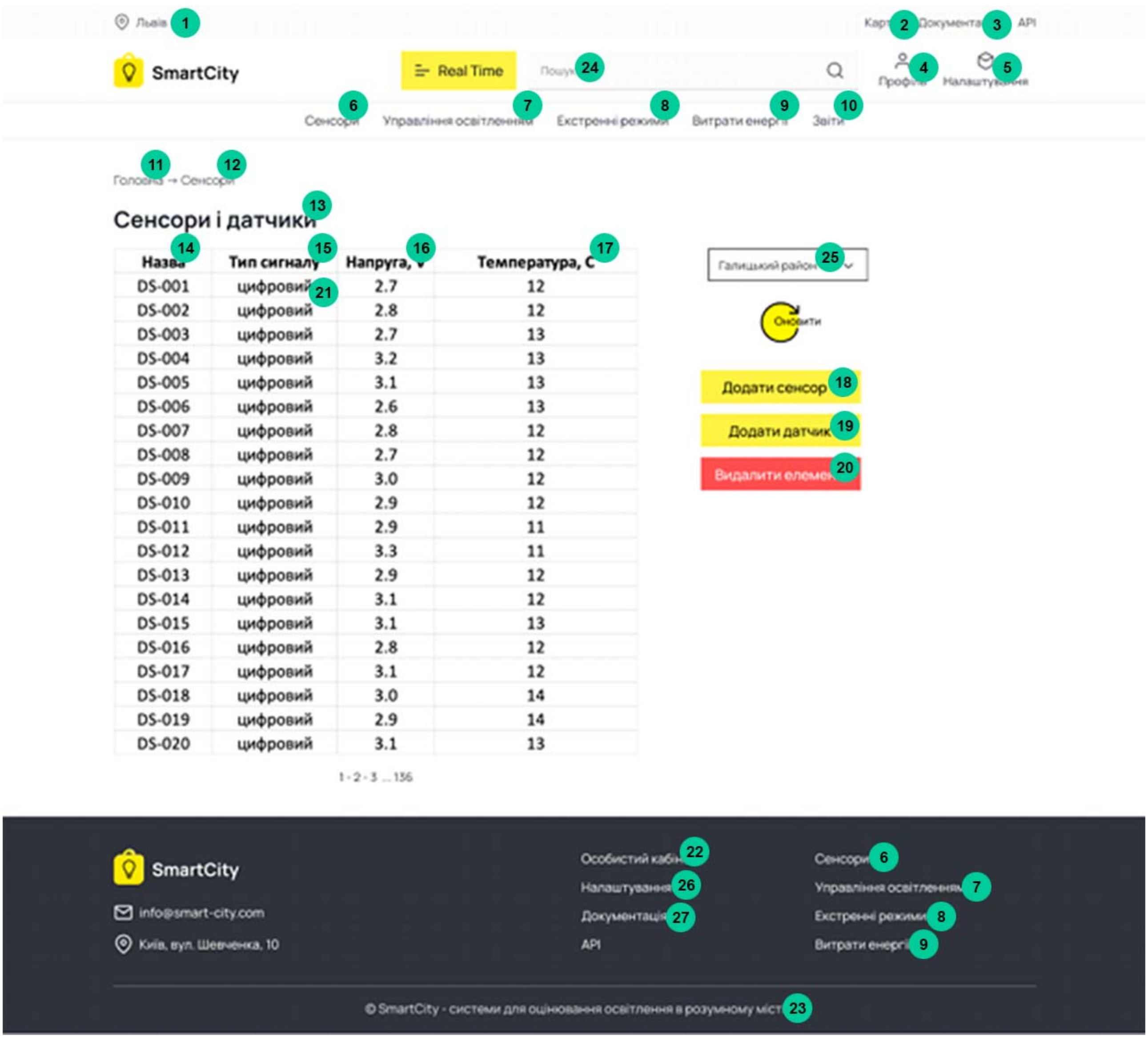

Figure 6 – Information system interface

1 – Lviv; 2 – map; 3 – documentation; 4 – profile; 5 – settings; 6 – sensors; 7 – lighting control; 8 – emergency modes; 9 – energy consumption; 10 – reports; 11 – main page; 12 – sensors; 13 – sensors and transmitters; 14 – name; 15 – signal type; 16 – voltage; 17 – temperature; 18 – add sensor; 19 – add transmitter; 20 – delete element; 21 – digital; 22 – personal account; 23 – a system for evaluating lighting in a smart city; 24 – find; 25 – Halytskyi district; 26 – Settings; 27 – documentation

of the lighting in a smart city, you can set the lighting schedule according to the needs of the city. For example, you can set the brightness to be increased during peak traffic hours and decrease it at night, when there are fewer people on the streets. In addition, it is necessary to consider that weather conditions, seasons, the presence of fog have a direct impact on the formation of lighting schedules.

4 EXPERIMENTS

It will be calculated the lighting schedule in accordance with the needs of the city. For example, you can set the brightness to be increased during peak traffic hours and decrease it at night, when there are fewer people on the streets.

It will be conducted a scenario with variable lighting brightness according to the needs of the city, taking into account peak traffic hours and nighttime.

Lighting schedule:

Peak traffic hours: 18:00 – 22:00 (4 hours).

Night time: 22:00 – 04:00 (6 hours).

Lighting intensity:

Peak hours: 20 lux.

Night time: 10 lux.

Number of lamps:

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Peak hours: 29.000 lamps·20 lux = 580.000 lamps*lux.

Nighttime: 29.000 lamps·10 lux = 290.000 lamps·lux.

Consumed energy:

It is assumed that each lamp has a power of 30 watts.

Energy consumption during peak hours: Energy=580,000 lamps·lux·30 W·4 hours=69.600.000 Wh or 69.600 kWh

Energy consumption at night: Energy=290.000 lamps·lux·30 W·6 hours=52.200.000 Wh or 52.200 kWh hours

Therefore, the total energy consumption per day for this scenario would be approximately 121.800 kWh.

These calculations are used for further optimization and analysis of the efficiency of the lighting system in a smart city and for the development of lighting schedules.

Let's consider an example of the response of the information system to changes in the intensity of traffic using a differential equation. It is supposed that the street lighting intensity $I(t)$ depends on the traffic on the street and reacts to its changes at different times of the year. It can be used the equation to describe the lighting dynamics (Formula 6):

$$D(t) = k \times I(t) + a \times R(t) . \quad (6)$$

The decrease in lighting intensity depends on the current level of lighting (attenuation) and increases with increasing traffic, the influence of the season, and the presence of fog.

It is appropriate to use Euler's method to solve this equation. Let's consider this on an example.

Initial conditions are $I(0) = 100$ (initial illumination level), $k = 0.01$ (attenuation coefficient), $a = 0.05$ (motion influence coefficient), $R(t)$ is the level of movement that can change over time. $R(t) = [5,10,15,8,12]$ and changes over time. It will be considered the array for saving the lighting intensity values $I(t) = [I,..0], t = 1$ is as a time step. It can be simulated the change in lighting intensity for 5 hours provided changing traffic levels on the street (Fig. 7).

The time of a year and the presence of fog can greatly affect the lighting schedule and the overall light level in the environment. Depending on the season, the factors that affect the duration and intensity of illumination in the dark time of a day change:

Duration of daylight. Depending on the season, the day can be shorter or longer, which leads to a change in the length of daylight and the hours with illumination at night.

Solstice angle. The angle of the solstice in the sky also changes with the season, which can affect how light falls on the ground and objects in the environment.

Light intensity. Sunlight can be more or less intense depending on the season, for example, in winter the light can be less bright due to more clouds or below the setting sun.

The presence of thick fog requires adjustment of the lighting intensity, which consists in the need to consider:

Scattering of light. Fog can scatter light, which leads to a decrease in its intensity and a decrease in the level of illumination in the environment.

Shading. Fog can also obscure lighting objects and reduce the amount of light that reaches the surface.

Lighting schedules are optimized to reduce energy consumption during low-traffic periods. Dynamic changes are displayed in graphs with the ability to adapt lighting schedules in real time based on changes in weather conditions, increase or decrease of activity in the lighting area, etc. The basis of the developed information system is an algorithm for monitoring and analyzing lighting data in different parts of the city, which provides for the continuous collection and processing of data for further improvement of schedules.

5 RESULTS

With the help of one of the methods of deep learning of recurrent neural networks (RNN) [15], particularly the Long Short-Term Memory (LSTM) layer for modeling temporal dependencies in time series made it possible to create a model for predicting street lighting needs. The information system starts forecasting LSTM uses a forgetting mechanism to avoid overloading its memory with unnecessary information.

1. Update login:

Forgetting: $f_t = \sigma(W_{xf} \times x_t + W_{hf} \times h_{t-1} + b_f)$.

Input: $i_t = \sigma(W_{xi} \times x_t + W_{hi} \times h_{t-1} + b_i)$.

Output: $o_t = (W_{xo} \times x_t + W_{ho} \times h_{t-1} + b_o)$.

2. Status update:

State candidate: $c_t = \tanh(W_{xc} \times x_t + W_{hc} \times h_{t-1} + b_c)$.

New state: $c_t = f_t \times c_{t-1} + i_t \times c_t$.

3. Exit Update:

Hidden state: $h_t = o_t \times \tanh(c_t)$,

where tanh is hyperbolic tangent.

An example of lighting calculations in a smart city using LSTM:

Conditional data:

The city is divided into 100 squares.

For each square we have data on:

Time of a day: 0–23 hours;

Day of the week: 0–6 (Sunday-Saturday);

Weather: sunny, cloudy, rainy;

Number of people: 0–1000;

Lighting level: 0–100 (lux).

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Problem is to predict the required level of illumination for each square for the next hour.

LSTM model:

Input data: time of a day, day of the week, weather, number of people.

Output data: predicted lighting level.

Number of layers: 2.

Number of neurons in layers: 128, 64.

Activation function: sigmoid.

Studies:

The model is trained on 70% of the data.

30% of the data is used for testing.

Results:

The model can predict the level of illumination with an accuracy of 90%.

The model can dynamically adjust the lighting depending on the environmental conditions and the number of people in each square.

A calculation example: Square: 50; Check-in time: 22:00; day of the week: 5 (Friday); Weather: cloudy; Number of people: 200.

Projected lighting level is 45 lux.

The conducted experiments demonstrate the effectiveness of the developed information system in planning and managing street lighting for different geographical zones of the city. Energy efficiency indicators and satisfaction levels of the population were balanced to achieve an optimal level of illumination.

We received the lighting schedule.

```
Hour 0: light intensity = 100.00
Hour 1: light intensity = 99.25
Hour 2: light intensity = 98.76
Hour 3: light intensity = 98.52
Hour 4: light intensity = 97.93
Hour 5: light intensity = 97.56
```

Figure 7 – Generated lighting schedule

The experiment results confirm the ability of the information system to effectively manage lighting, leading to a reduction in electricity consumption and promoting sustainable urban development. The experiments validate the improvement in residents' quality of life by providing optimal street lighting levels according to their needs and the time of day. Additionally, a decrease in pedestrian-involved accidents and crimes due to increased visibility on the streets has been observed.

The experimental research also includes an analysis of technical system indicators such as reliability, responsiveness to changing conditions, compatibility with existing city infrastructure, and more. Therefore, the experiment results confirm the effectiveness and benefits of implementing the street lighting management information system in a smart city in terms of energy efficiency, safety, and economic viability.

6 DISCUSSION

The advantages of using LSTM for lighting calculations are the ability to predict the level of illumination with high accuracy; dynamically adjust the lighting depending on the conditions of the surrounding environment and the number of people moving on the street; save energy by using lighting only when it is needed.

Monitoring and data collection takes place with the help of sensors located in different parts of the city to measure energy consumption and collect data on the state of lighting and with the help of the Internet of Things and fog technologies. The implementation of the information system was carried out in the Python language using the library for working with the MQTT protocol.

The written code uses a simple MQTT client to connect to the central system via the MQTT protocol. The client subscribes to the "ligh-ing/commands" topic to receive commands from the central system and publishes lighting status reports to the "lighting/report" topic. The reports contain information about the lighting area and the current brightness level.

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CONCLUSIONS

The project on the creation of the information system designed to provide an energy-efficient lighting system in a smart city will contribute to increasing security, in particular, ensuring the safety of the community through integration with security systems, reducing energy consumption, through minimizing the use of electricity in periods when the need for lighting is not necessary.

It was determined that in order to implement an information system for remote monitoring and control of lighting in a smart city, it is advisable to consider the possibility of using a complex lighting control system. Calculations were made on the example of Lviv for the city's lighting needs. The use of motion detectors to determine the need to turn on lighting is analyzed. A conceptual model of the information system was developed using the object-oriented methodology of the UML notation. The main functionality of the information system is defined.

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ІНФОРМАЦІЙНА СИСТЕМА КОНТРОЛЮ ВУЛИЧНОГО ОСВІТЛЕННЯ У РОЗУМНОМУ МІСТІ

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АНОТАЦІЯ

Актуальність. У контексті стрімкого розвитку технологій та впровадження концепції смарт-сіті, розумне освітлення стає ключовим елементом сталого та ефективного міського середовища. Дослідження охоплює аналіз аспектів використання давачів, інтелектуальних систем управління освітлення з допомогою сучасних інформаційних технологій, зокрема таких як Інтернет речей. Застосування таких технологій дозволяє автоматизувати регулювання інтенсивності освітлення в залежності від зовнішніх умов, руху людей чи часу доби. Це сприяє ефективному використанню електроенергії та зниженню викидів в атмосферу.

Мета роботи полягає в аналізі процедур створення інформаційної системи, як інструменту моніторингу та оцінювання рівня освітленості в розумному місті з метою покращення енергоефективності, безпеки, комфорту та ефективного управління освітленням. Реалізація системи розумного освітлення для міста Львова сприятиме покращенню енергоефективності та безпеки громади.

Метод. Проведено контент-аналіз наукових публікацій, в яких подано результати дослідження щодо створення систем моніторингу вуличного освітлення в реальних міських середовищах. Проведено збір та аналіз даних про вуличне освітлення в місті, таких як енергоспоживання, рівень освітленості, графіки роботи світильників та інші. Використано методи машинного навчання для аналізу даних та прогнозування потреб в освітленні. З використанням методології UML розроблено концептуальну модель інформаційної системи моніторингу вуличного освітлення на основі виявлених потреб і вимог.

Результати. Висвітлюється роль технологій опрацювання даних у створенні ефективних стратегій управління освітленням для оптимального використання ресурсів та задоволення потреб містян. У дослідженні звертається увага на виклики та

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можливості впровадження розумного освітлення у містах, максимізації позитивного впливу розумного освітлення на сучасні міські середовища. Проаналізовано особливості розроблення та використання інформаційної системи для контролю вуличного освітлення в розумному місті. Визначено потенційні переваги та обмеження використання розробленої системи.

Висновки. Проект із створення інформаційної системи, що покликана забезпечити енергоефективну систему освітлення в розумному місті, сприятиме підвищенню безпеки, зокрема, забезпечення безпеки громади через інтеграцію з системами безпеки, зменшення енергоспоживання, через мінімізацію використання електроенергії в періоди, коли потреба освітлення не є необхідною.

Визначено, що для реалізації інформаційної системи дистанційного моніторингу та управління освітленням в розумному місті, доцільно розглянути можливість використання комплексної системи управління освітленням. Проведено розрахунки на прикладі Львова потреби освітленні міста. Проаналізовано використання давачів руху для визначення необхідності увімкнення освітлення. Розроблена концептуальна модель інформаційної системи з використанням об'єктно-орієнтованої методології нотації UML. Визначено основний функціонал інформаційної системи.

КЛЮЧОВІ СЛОВА: інформаційна система, система освітлення, розумне місто, дистанційний моніторинг, прогнозування.

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METHODS FOR ANALYZING THE EFFECTIVENESS OF INFORMATION SYSTEMS FOR INVENTORY MANAGEMENT

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ABSTRACT

Context. Information systems for inventory management are used to forecast, manage, coordinate, and monitor the resources needed to move goods smoothly, in a timely, cost-effective, and reliable manner. The more efficiently the system works, the better results a company can achieve. A common problem with existing performance measurement methods is the difficulty of interpreting the relationship between performance indicators and the factors that influence them.

Objective. The purpose of the study is to describe a method for evaluating the effectiveness of information systems, which allows to establish a link between performance indicators and factors that influenced these indicators.

Method. A set of indicators characterizing the effective operation of inventory management information systems is proposed. The rules for quantifying the factors that influence the performance indicators are proposed. The factors arise during events that affect the change in order, delivery, balance, target inventory level, parameters of the forecasting algorithm, etc. The proposed method performs an iterative distribution of the quantitative value of factors among performance indicators and thus establishes the relationship between performance indicators and factors.

Results. The implementation of the proposed method in the software was carried out and calculations were made on actual data.

Conclusions. The calculations carried out on the basis of the method have demonstrated the dependence of performance indicators on factors. The use of the method allows identifying the reasons for the decrease in efficiency and making the company's management more efficient. Prospect for further research may be to detail the factors, optimize software implementations, and use the method in inventory management information systems in various areas of activity.

KEYWORDS: inventory management efficiency, information system, management system, evaluation methods, factors, Big Data.

ABBREVIATIONS

COVID-19 is coronavirus disease 2019;

AI is artificial intelligence;

ISIM is information system for inventory management.

NOMENCLATURE

T_t is a target level of inventory;

f_t is a forecast demand;

d_t is a demand;

m_t is a forecast error;

q is a quantity of goods for visual representation on the shelf (or product display);

L_t is lost sales;

O_t is an overstock;

I_t is a balance in period t;

$\hat{I}_t$ is a balance in period t, taking into account the influence of factors;

l is a order fulfillment time;

c is a cyclical replenishment of goods;

Q_{t-l} is a quantity ordered at the beginning of period $t–l$ (which will arrive at the beginning of period t);

Q_t is a quantity ordered that arrived at the beginning of period t;

R_t is a set of factors in period t;

k is a number of factors that influenced the efficiency of the inventory management information system in period t;

n is a serial number of the factor occurrence;

id_i is a identifier of the factor characterizing the cause of its occurrence;

r_i is a quantitative value of the factor;

CR_t is a set of factors that influenced the performance indicator in period t;

cr_i is a quantitative value of the factor that influenced the performance indicator;

idL_i is a percentage of lost sales affected by the factor id_i;

idO_i is a percentage of overstock influenced by the factor id_i;

p is a purchase price;

s is a sale price;

$x^+ = \max(0; x)$.

INTRODUCTION

In a dynamic market, under the influence of external factors, or when scaling a business, effective inventory management is one of the key success factors [1]. Consumer demand can fluctuate at different stages of the supply chain for many reasons, such as inventory management strategy, forecasting methods, order processing time, and other factors. In addition, during the COVID-19 pandemic and the war, supply chains have faced a significant increase in unreliable order fulfilment. This leads to disruptions in the movement of information and material flows, violating the main goal of the work – to meet the needs of both their own and customers [5, 15].

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That's why more and more companies are implementing special information systems and specialized software to help them optimize and control stocks of goods, raw materials, supplies, and other resources.

Information systems and software for inventory management work with large amounts of data, collect data on sales, inventory, deliveries, and other indicators, automate forecasting and ordering processes, and offer data analytics. Mathematical methods of extrapolation and regression, as well as machine learning, are used for forecasting [10].

There are various methods for evaluating the effectiveness of an ISIM, which can be divided into two groups – quantitative and qualitative methods.

Quantitative methods:

– Inventory level analysis – whether the inventory level is optimal to minimize storage costs and the risk of spoilage, and to guarantee uninterrupted trading.

– Inventory turnover analysis – how many times in a certain period the inventory is renewed. High turnover indicates effective inventory management.

– Analysis of storage costs – what are the costs associated with storing inventory, such as warehouse rent, utilities, insurance, and others.

– Analysis of the level of lost sales – how many sales were lost because the demand for the product exceeded its availability. A low level of lost sales indicates effective demand forecasting.

– Analysis of the overstock level – what is the level of inventory that is not expected to be sold within a certain period of time.

– Analysis of demand forecasting accuracy – assessment of forecasting accuracy using various metrics such as MAPE, MAE, ME, MSE, RMSE, and others.

Qualitative methods:

– Assessment of the level of customer service. This method assesses how satisfied customers are with the availability of goods.

– Assessment of warehouse logistics efficiency. This method assesses how well warehouse processes, such as receiving goods, storage, shipping, and inventory, are organized.

– Data quality assessment. This method assesses how accurately and completely the information system collects data on sales, inventory, deliveries, and other indicators.

– Ease of use assessment. This method assesses how easy it is to use the inventory management information system.

To assess the effectiveness of an ISIM, a comprehensive approach is used that takes into account both quantitative and qualitative methods, for example:

– ABC-XYZ analysis is a classification of goods by their importance and turnover to focus on the most important items.

– Benchmarking – comparing the company's performance with industry benchmarks.

– Audit – conducting inspections and inviting various consultants to analyze the results of the inventory management system.

– Customer surveys – collecting and analyzing customer feedback on the level of service.

The effectiveness of an ISIM is influenced by many factors, including the reliability of suppliers, logistical constraints and company policies, forecast accuracy, energy supply, data quality, and others..

The object of study is the process of evaluating the effectiveness of the ISIM. Information systems and software for inventory management work with large amounts of data, which makes the process of performance evaluation time-consuming. This is due to an extensive information storage system, different assessment rules in different departments, and employee interference with automated processes. Therefore, to increase the speed of analysis, unified rules for quantifying the factors that affect performance indicators are needed.

The subject of study is the methods for assessing the effectiveness of inventory management systems. A common problem of the known methods is the complex interpretation of the reasons that influenced the performance indicators.

The purpose of the work is to establish a link between the performance indicators of inventory management information systems and the factors that influence these indicators.

1 PROBLEM STATEMENT

Suppose that there is a set of factors R_t that affect the performance indicators of the ISIM in period t:

$$R_t = \begin{bmatrix} id_1 & id_2 & ... & id_k \\ n_1 & n_2 & ... & n_k \\ r_1 & r_2 & ... & r_k \end{bmatrix}. \quad (1)$$

For a performance indicator for a given set of factors R_t, it is necessary to build a correspondence matrix CR_t, which shows the relationship between the performance indicator and the factors that influenced it:

$$CR_t = \begin{bmatrix} id_1 & id_2 & ... & id_k \\ cr_1 & cr_2 & ... & cr_k \end{bmatrix} \quad (2)$$

2 REVIEW OF THE LITERATURE

In [1] is proved that the company's performance depends on the efficiency of inventory management. This conclusion is robust to the use of different evaluation methods. The level of inventories is a key factor in the effectiveness of the ISIM and depends on the chosen management methods, demand, and the impact of external and internal factors of the company.

In [2, 3] studied the impact of management methods on inventory levels. In particular, [2] investigates the impact of the ABC analysis method, the level of inventory controlled by the supplier and the periodic review approach on the level of inventory. In [3], a method of reducing inventory levels through the use of ABC-XYZ analysis is investigated, the process of assortment plan-

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ning, ordering and inventory management is analyzed. The importance of monitoring inventory movement to achieve optimal inventory levels, as well as the results and recommendations for future operations are presented.

Various forecasting methods are used to ensure that the level of stocks corresponds to consumer demand. In [4], the role of demand forecasting in a business intelligence system is considered. High forecast accuracy helps to formulate a sustainable market strategy, increase inventory turnover, reduce supply chain costs, and increase customer satisfaction. Demand for a particular product or service is usually associated with various uncertainty factors that can make it unstable and difficult to predict. Errors in demand forecasting and their dependence on various factors are discussed in [5]. Given the diversity of demand forecasting methods, it is unlikely that any single method of demand forecasting can provide the highest forecasting accuracy for all products. Approaches for automated model selection for retail demand forecasting based on economic profitability, taking into account lost sales and inventory costs, are presented in [6–8].

The use of artificial intelligence (AI) is gaining wide application in forecasting. The authors of [9] consider the role of AI in inventory management and identify challenges in implementing AI, such as data quality, interpretability, and model transparency.

The main task of any forecasting algorithm is to obtain results with a minimum forecast error. The use of forecasting algorithms implies a linear development of events: calculation of the forecast, creation of an order based on the forecast, fulfilment of the order by the supplier on time and in full, timely placement of goods on the store shelf, no disruptions in the store itself, etc. However, there is some uncertainty in the development of events caused by the influence of external factors and internal rules and policies of the company, so it is difficult to find solutions to real-life problems in a precise form. This directly affects the result of calculating the forecast quality indicators [10].

An analysis of external and internal factors affecting the effectiveness of the ISIM is given in [11–14]. The factors include the economic situation, reliability of suppliers, delivery time, quality of internal production operations, level of process automation, logistics rules and policies, etc. However, the articles do not provide rules for calculating the quantitative impact of factors on the effectiveness of the ISIM. Thus, the available methods provide an indirect link between the result of the inventory management system and the factors that influenced it.

3 MATERIALS AND METHODS

In this article, the authors propose a method that will allow establishing a link between the results of the assessment of the effectiveness of the ISIM and the factors that influenced these results.

The ISIM automates the forecasting and ordering process, thus influencing the availability of goods. To forecast demand, raw sales data is first collected from the market, and then the future demand for the product is forecasted according to the data [4]. The efficient operation of the system is when there is neither too little nor too much of the product. An indicator of effective operation is the presence of a balance I_t that does not exceed the target inventory level T_t, i.e. the amount required for sales and visual representation of the product. The target inventory level T_t is proposed to be calculated by the formula:

$$T_t = \sum_{i=t}^{t+l+c} f_i + q. \tag{3}$$

It is proposed to use lost sales L_t and overstock O_t as quantitative indicators of performance evaluation.

Lost sales are sales that did not take place because the product was unavailable, i.e., the stock I_t for the product is zero. Lost sales are equal to the demand d_t in period t minus the existing inventory level for the previous period I_{t-1} and the order quantity Q_t for the last period [16]:

$$L_t = (d_t - I_{t-1} - Q_t)^+. \tag{4}$$

Overstock is inventory that exceeds the target inventory level T_t:

$$O_t = (I_t - T_t)^+. \tag{5}$$

Lost sales and overstock can be expressed in both absolute and relative terms, i.e. as an amount or percentage of total sales and inventory, respectively.

The values of lost sales and overstock depend on the balance. Therefore, we will further consider what influences the inventory balance. The level of inventory in period t upon receipt of an order is proposed to be determined as follows:

$$I_t = (I_{t-1} + Q_{t-l} - d_t)^+ = (I_{t-l} + Q_{t-l} - \sum_{i=t-l}^{t} d_i)^+ \tag{6}$$

Then, the order is determined by the formula:

$$Q_{t-l} = (\sum_{i=t-l}^{t+c} f_i + q - I_{t-l})^+. \tag{7}$$

In this case, the forecast can be represented by the demand and the forecast error [5] as:

$$f_i = d_i + m_i \tag{8}$$

The ideal model of the ordering and replenishment cycle can be described as follows: the ISIM makes a forecast and calculates the quantity for the order of goods, the order is fulfilled by the supplier on time and in full, it appears in the store on time and sales data is received by the information system on time and without distortion. Therefore, in this case, the level of inventory in the period between delivery and the next delivery is proposed to be defined as:

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$$I_t = \begin{cases} \left(\sum_{i=t}^{t+c} f_i + \sum_{i=t-l}^{t} m_i + q \right)^+, if \sum_{i=t}^{t+c} f_i + q \ge I_{t-l} \\ \left(I_{t-l} - \sum_{i=t-l}^{t} (f_i + m_i) \right)^+, else. \end{cases} \quad (9)$$

In an ideal order cycle model, the forecast f_i is a constant value, i.e., the variability of the stock I_t depends only on the forecast error m_i. With an absolutely accurate forecast, the stock balance will fluctuate between the quantity of goods for visual display on the shelf q and the target inventory level T_t. Lost sales L_t will be caused by an insufficient forecast, i.e., when m_i is negative, and overstock O_t will be caused by an over-forecast, i.e., when m_i is positive.

However, events during the ordering and replenishment cycle do not unfold linearly: the supplier may not have the goods or they may not be available in full quantity, the delivery may be late, the goods may be damaged, etc. In other words, the goods will not be available on the store shelf in the required quantity and at the required time not only because of the forecast error, but also due to certain external and internal factors. These factors can be grouped as follows:

– Logistics rules and policies of the company (order multiplicity, minimum delivery batch, financial restrictions, etc.)

– Reliability of the supplier (the supplier may be late, deliver the goods incompletely, not at all, or deliver more than ordered)

– Data in the system (errors in document data can be corrected "retroactively", outdated data in the central database, communication, etc.)

– Receiving, processing and sending an order to a store may be delayed due to a shortage of warehouse workers

– Decrease in the balance not related to sales (write-offs, thefts, transfers to other divisions, inaccurate information about the balance when ordering, etc.)

– Manual order adjustment.

Factors have a certain order of occurrence and affect changes in the inventory balance, order, delivery, or target inventory level. That is, each factor can be quantified. The set of factors in period t can be represented as the matrix R_t (1).

Taking into account the influence of the factors, the inventory level in period t is proposed to be determined as follows:

$$\hat{I}_t = \begin{cases} \left(\sum_{i=t}^{t+c} f_i + \sum_{i=t-l}^{t} m_i + q + \sum_{i=t-l}^{t} r_i \right)^+, if \sum_{i=t}^{t+c} f_i + q \ge I_{t-l} \\ \left(I_{t-l} - \sum_{i=t-l}^{t} (f_i + m_i + r_i) \right)^+, else. \end{cases} \quad (10)$$

Thus, both an insufficient forecast and a negative value of r_i will lead to lost sales, and both an excessive forecast and a positive value of r_i will lead to overstock. The task of the method is to establish a link between the values of lost sales L_t, overstock O_t and the quantitative values of the factors r_i.

The link between the factors R_t and lost sales L_t or overstock O_t is represented in the form of the correspondence matrix CR_t (2).

To determine the factors that led to the appearance of lost sales L_t, is need to:

1. Determine the nearest order that was to be delivered before the date of the lost sale (Fig. 1)

2. Determine the events that led to a decrease in backlog, delivery, or balance from the date of the order that was to be delivered to the date of the lost sale.

3. For each of the events, determine the cause id_i, calculate the factors r_i and the order of their occurrence n_i. Examples of calculating factors are given in the section "Experiments"

4. Determine the factors that influenced L_t using algorithm 1. The influence of a factor on lost sales is limited in quantity. That is, if the factor r_i influenced the lost sales of L_t in the amount of cr_i, then the lost sales of L_{t+1} are influenced in an amount not exceeding $r_i - cr_i$

5. If the value of L_t is greater than the total value of the factors $\sum r_i$, then the reason for the difference $L_t - \sum r_i$ – forecast error.

Algorithm 1. Determine the factors that influenced the lost sales L_t

Input: Lost sale L_t, factor matrix R_t[id,n,r]
Output: correspondence matrix CR_t[id,cr]

```
L_value ← Lt
WHILE L_value>0 AND EXISTS ri>0, i = 1,2,…,k
   #find index of first event with positive ri
   min_i ← GET_INDEX(for ri>0 MIN(ni))
   r_value ← MIN(rmin_i;L_value)
   CRt[id,cr] ← (idmin_i,r_value)
   Rt[rmin_i] ← rmin_i – r_value
   L_value ← L_value – r_value
END WHILE
IF L_value>0
   #forecast error
   CRt[id,cr] ← (idforecast_error, L_value)
END IF
RETURN CRt
```

In order to determine the factors that led to the overstock O_t, it is necessary:

1. Determine whether the events led to an increase in the balance or a decrease in the target T_i level. Identification and calculation of events that led to an increase in the balance or a decrease in the target level should be carried out in descending order of dates from the overstock (Fig. 2).

2. Determine the cause id_i for each of the events, calculate the factors r_i and the order of their occurrence n_i. Examples of calculating factors are given in the section "Experiments"

3. Determine the factors that influenced O_t using algorithm 2.

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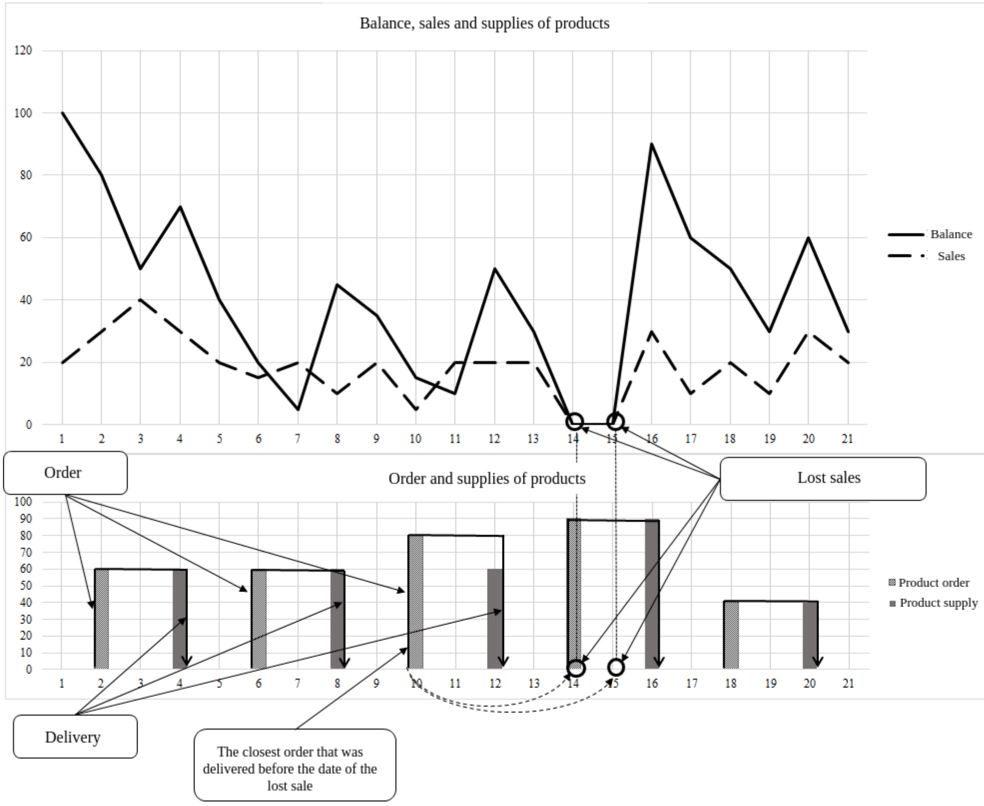

Figure 1 – The closest order that should have been delivered to the date of the lost sale

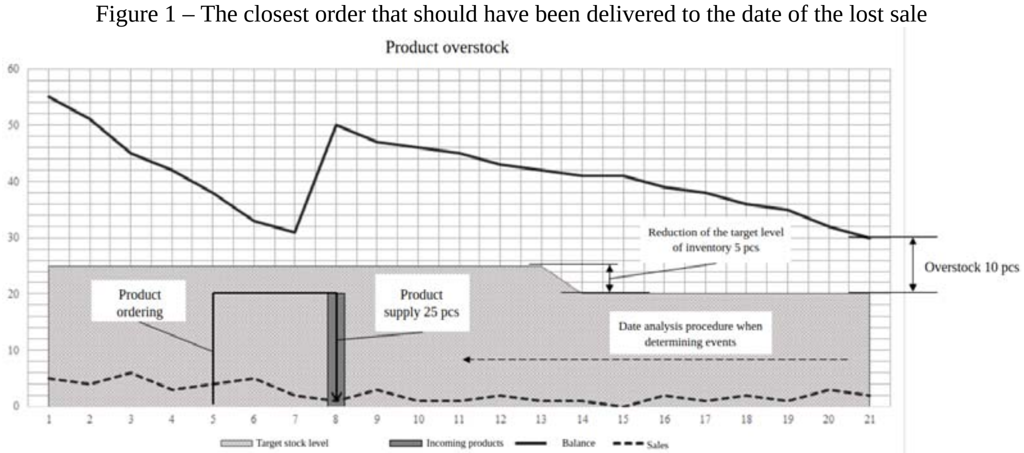

Figure 2 – Events that led to overstock

Algorithm 2. Determine the factors that influenced the overstock O_t

Input: overstock O_t, factor matrix R_t[id,n,r]
Output: correspondence matrix CR_t[id,cr]

1. O_value ← O_t
2. **WHILE** L_value>0 AND EXISTS r_i>0, i = 1,2,…,k
3. #find index of first event with positive r_i
   min_i ← GET_INDEX(for r_i>0 MIN(n_i))
4. r_value ← MIN(r_{min_i};O_value)
5. CR_t[id,cr] ← (id_{min_i},r_value)
6. O_value ← O_value – r_value
7. **END WHILE**
8. **RETURN** CR_t

4 EXPERIMENTS

Below are the factors that can cause lost sales or overstock and how they are calculated. The list of factors is provided to understand the principle of their calculation, it can be expanded or adjusted depending on the specifics of the organization of business processes in a particular company.

To quantify the factors that affect lost sales L_t, must be calculated:

1. Reducing the Q_t order at the stage of order formation and fulfilment.

2. Reduction of the I_t balance, which was not taken into account when ordering due to damage to the goods, theft, transfer to another unit or store.

3. Reduction of Q_t order due to forecast error f_i.

In order to quantify the factors on which the overstock O_t depends, it is necessary to identify:

1. What events led to the increase in the It balance. To do this, it is necessary to determine the increase in orders or deliveries relative to the initial order Q_t.

2. What events led to a decrease in the target level of T_t.

Examples of quantitative calculation of factors are given in Table 1.

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Table 1 – Examples of quantitative calculation of factors

Efficiency indicator	Stage	ID	Factor description	Calculation example
Lost Sales	Order formation	id_1	reducing the order to ensure multiplicity	the initial order was 120 units, while the order multiplicity is 100 units, so only 100 units were ordered, r_1= 20 units
		id_2	reducing the order to secure the logistics batch	the initial order was 50 units, the total weight of the order to the supplier was 23 tons, while the logistics batch is 20 tons, so only 40 units were ordered, in this case r_2= 10 units
		id_3	order reduction due to financial constraints	the initial order was 50 units, but due to lack of funds, the goods were not ordered, then r_3 = 50 units
		id_4	reduction or cancellation of the order manually by the manager	the initial order was 500 units, but the manager reduced the need and an order of 100 units was sent to the supplier, then r_4 = 400 units
	Order fulfilment	id_5	the supplier fulfilled the order in a smaller quantity than was ordered	100 units were ordered from the supplier, but only 70 units were delivered, then r_5 = 30 units
		id_6	delivery took place later than scheduled.	this case applies only to those days with lost sales that occurred between the scheduled delivery date and the date of actual receipt of the goods. In this case, r_6 is equal to the total amount of the delayed order. For example, 100 units were ordered on Friday and were to be delivered on Saturday. But the delivery took place only on Tuesday. Sales were lost on Sunday and Monday. Then for the lost sales on Sunday and Monday r_6 = 100 units
	Reducing the balance	id_7	reducing the balance of goods as a result of moving to other units or stores, if the possibility of such movements is not taken into account in the forecasting algorithm	the store has a bakery, for which flour is supplied separately. The finished products were quickly sold out and the bakery did not have enough flour available, so they took 100 kg of flour from the store shelf, then r_7 = 100 kg
		id_8	reduction of the balance of goods due to spoilage	5 units were written off due to the expiration date, then r_8 = 5 units
		id_9	reducing the balance of goods as a result of the inventory	during the inventory, it was found that the actual balance of the goods is 0 pcs. and there are 15 units in the system, then r_9 = 15 units
		id_{10}	reducing the balance of goods due to inaccurate information in the information system	the balance of the goods was 100 units, of which 20 units were sold, but due to the lack of communication, this information was not received by the information system, i.e. the order was made based on the amount of the balance of 100 units, although the actual balance was 80 units, then r_{10} = 20 units
	Forecast error	id_{11}	between the date of the order and the date of the lost sale, the parameters were changed, which resulted in a lower forecast at the time of the order	at the time of the order, the sales forecast was 100 units, but after the order, the price of the goods was reduced due to the start of pro-activity, and the updated sales forecast, taking into account the price reduction, was 300 units, then r_{11} = 200 units
		id_{12}	forecast inaccuracy, which is not related to the parameters of the forecast algorithm, i.e. an increase in demand that the algorithm cannot predict	the outbreak of the COVID-19 pandemic led to a sharp panic increase in demand, which resulted in empty store shelves. The number for this reason is equal to the difference between the lost sales and the sum of all other reasons related to a particular order. That is, the amount of lost sales that is not covered by other reasons should be attributed to r_{12}
Overstock	Order formation	id_{13}	increasing the order to ensure multiplicity	the initial order was 70 units, while the order multiplicity is 100 units, so 100 units were ordered, in this case r_{13} = 30 units
		id_{14}	increasing the order through a logistics batch	the initial order was 50 pieces, the total weight of the order to the supplier was 17 tons, while the logistics batch is 20 tons, so only 90 pieces were ordered, in this case r_{14} = 40 units
		id_{15}	increase the order manually by the manager	the inventory balance was sufficient, so the initial order was 0 units, but the manager decided to order the goods and the supplier was sent an order in the amount of 500 units, then r_{15} = 500 units
	Order fulfilment	id_{16}	the supplier fulfilled the order in a larger volume than was ordered	100 units were ordered and 150 units were delivered, then r_{16} = 50 units
	Balance increase	id_{17}	increase the balance of goods as a result of moving from another store or unit, if the possibility of such movements is not taken into account in the forecasting algorithm	the balance of a neighboring store were moved to the store as a result of its closure
		id_{18}	Increase in the balance of goods as a result of the inventory, for example, when a re-sort is detected	during the inventory, it was found that the actual balance of the goods is 50 pieces, and there are 10 pieces in the system, then r_{18} = 40 units
		id_{19}	data errors, increase in overstock due to inaccurate information in the information system	the delivery of goods in the amount of 200 units was not entered into the system in time, which resulted in the re-formulation of an order for 200 units, which was fulfilled, then r_{19} = 200 units
	Target level reduction	Id_{20}	reducing the quantity for visual representation of the product	at the end of the season, the number of items on the shelf decreases from 50 to 10, resulting in a target level of 40 units, then r_{20} = 40 units
		id_{21}	reduction of order multiplicity	the product was delivered to the store only in multiples of boxes of 40, but a decision was made to order by the piece, as a result of which the target level decreased from 40 to 25, then r_{21} = 15 units
		id_{22}	forecast error, reduction of the target level due to changes in the parameters of the forecasting algorithm	after the order was placed, the price of the product was increased, resulting in a decrease in demand for the product, which led to a decrease in the target level from 80 units to 30 units. In this case r_{22} = 50 units
		id_{23}	reduction of the target level due to a decrease in demand, which is not related to the parameters of the forecast algorithm	an unpredictable decline in demand for the product resulted in the target level being reduced from 150 units to 70 units, then r_{23} = 80 units

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The following functionality has been implemented in the inventory management information system to collect data on the factors of influence:

– order and delivery schedules;

– link between the order and the delivery, i.e., which order was delivered, and whether the delivery was late;

– order parameters – initial order, fixing order changes when applying multiplicity, logistics batch, financial constraints, order adjustment by the manager;

– storing the history of changes in the parameters of the forecasting algorithm, the quantity for visual representation, and the order multiplicity;

– ability to recalculate the order and target inventory level with changed parameters.

5 RESULTS

The method was tested on actual data. The data for 2023 of one of the Ukrainian retail chain selling cosmetics, perfumes, care and health products were analyzed. The chain consists of 1072 stores and has an average of 8 thousand products in its assortment. The data is presented on the condition of company anonymity.

For each product at each storage point, the values of performance indicators were calculated: lost sales L_t and overstock O_t. The lost sales were calculated for each day, and overstock for the end of each week of the analysis period.

Software was developed to collect data on the id_i influence factors. Using the rules described in the “Experiments” section, the quantitative values of the r_i factors were calculated. According to the method described above, the relationship between the id_i factors in the amount of cr_i, lost sales L_t and overstocks O_t was established. The results obtained on the influence of factors on performance indicators were converted into percentages.

The percentage of lost sales influenced by the id_i factor is calculated by the formula:

$$idL_i = \sum cr_i \cdot s \Big/ \sum L_t \cdot s \cdot 100\%. \qquad (11)$$

The percentage of overstock influenced by the id_i factor is calculated by the formula

$$idO_i = \sum cr_i \cdot p \Big/ \sum O_t \cdot p \cdot 100\%. \qquad (12)$$

The values of lost sales L_t, overstock O_t, and the quantitative values of factors r_i and cr_i in monetary and quantitative terms are not given due to commercial secrecy. Table 2 shows the results of the calculation of the percentage of lost sales and overstock affected by each factor.

Table 2 – Influence of factors on the performance indicators of the inventory management information system

Indicator	Factors	Influence of the factor, %
Lost sales	The supplier fulfilled the order in a smaller volume	22.3%
	Reducing or cancelling an order manually by a manager	22.1%
	Forecast error	15.5%
	Adding a new product to the assortment	10.8%
	Sharp increase in demand (aftermath of shelling)	8.5%
	Reducing the order to ensure multiplicity	5.8%
	The delivery took place later than scheduled	5.6%
	Promotional activity	3.5%
	Order reduction for a logistics batch	2.4%
	Decrease in the balance due to inaccurate information in the information system	1.2%
	Other reasons	2.2%
Overstock	Manual order increase by the manager	31.6%
	Increasing the order for a logistics batch	20.8%
	Promotional activity	17.0%
	Data errors	11.5%
	Removing a product from the assortment	7.0%
	Reducing the quantity for visual representation of the producty	5.4%
	Forecast error	2.9%
	Increase the order to ensure multiplicity	2.1%
	The supplier fulfilled the order in a larger volume than was ordered	1.1%
	Other reasons	0.7%

6 DISCUSSION

According to the results obtained, only 15.5% of lost sales and 2.9% of overstocks depend on the accuracy of the forecast. That is, improving the forecasting algorithm will have a limited impact on the efficiency of the inventory management information system. A small percentage of the forecast’s impact on the efficiency of inventory management is explained by external factors and internal company rules. Thus, to increase efficiency, it is necessary to control and measure all processes that affect the availability of goods in the right quantity and in the right place.

Due to the fact that all calculations in the method were made in the context of specific products and stores, further analysis can be carried out in different sections, for example, by suppliers, regions, supply routes, individual stores, product groups, product category managers, etc. For each breakdown, it is possible to identify the biggest causes and specific items that lead to losses and compare the losses with the cost of solving the problem.

It should also be noted that the automation of data collection on impact factors and computations make it possible to conduct analysis on a regular basis and take into account the dynamics of changes in the impact of factors. This allows for a quick assessment of the impact of decisions made on the effectiveness of the ISIM.

CONCLUSIONS

The study proposes a new method for evaluating the effectiveness of information systems, which allows estab-

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lishing a link between performance indicators and the factors that influenced these indicators.

Based on actual data, the study calculates the impact of factors on lost sales and surplus of one of the Ukrainian retail chains. The result of the company's work depends on the efficiency of the inventory management information system. Various factors affect the effectiveness of the system: company policies and rules, logistical and financial constraints, supplier reliability, and forecast accuracy. It is shown that improving the forecast algorithm has a limited impact on the efficiency of the inventory management information system.

The scientific novelty of obtained results is that for the first time a method for analyzing the effectiveness of inventory management information systems has been proposed, which allows establishing a link between lost sales, excess inventory and the factors that influenced these results. This makes it possible to automate the analysis and perform it for different data sections and reduce the time for making management decisions

The practical significance of obtained results lies in the fact that the rules for calculating the factors and the necessary functionality of the inventory management information system have been formed, software that implements the proposed method has been developed, and the method has been applied to real data. The results of the experiments allow us to recommend the use of the method for systematic identification of the causes of efficiency reduction in practice**.**

Prospects for further research is to study the results of the method for a wider range of practical tasks.

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МЕТОДИ ДЛЯ ПРОВЕДЕННЯ АНАЛІЗУ ЕФЕКТИВНОСТІ ІНФОРМАЦІЙНИХ СИСТЕМ ДЛЯ УПРАВЛІННЯ ЗАПАСАМИ

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АНОТАЦІЯ

Актуальність. Інформаційні системи управління запасами використовуються для прогнозування, керування, координації та моніторингу ресурсів, необхідних для плавного, своєчасного, економічно ефективного та надійного переміщення товарів. Чим ефективніше працює система, тим кращі результати може здобути компанія. Загальною проблемою наявних методів оцінки ефективності є складна інтерпретація зв'язку показників ефективності з факторами, які на ці показники вплинули.

Мета. Метою роботи є опис методу для оцінки ефективності інформаційних систем, що дозволяє встановити зв'язок між показниками ефективності та факторами, що вплинули на ці показники.

Метод. Запропоновано набір показників, що характеризують ефективну роботу інформаційних систем управління запасами. Запропоновано правила для кількісного обчислення факторів, що впливають на показники ефективності. Фактори виникають під час подій, що впливають на зміну замовлення, постачання, залишку, цільового рівня товарного запасу, параметрів алгоритму прогнозування, тощо. Запропонований метод виконує ітераційний розподіл кількісного значення факторів серед показників ефективності і встановлює таким чином зв'язок між показниками ефективності та факторами.

Результати. Виконано реалізацію запропонованого методу у програмному забезпеченні та проведено розрахунки на фактичних даних.

Висновки. Проведені на основі методу розрахунки продемонстрували залежність показників ефективності від факторів. Використання методу дозволяє виявляти причини зниження ефективності та робити управління компанією більш оперативним. Перспективою подальших досліджень може бути деталізація факторів, оптимізація програмних реалізацій та використання методу в інформаційних системах управління запасами різних напрямків діяльності.

КЛЮЧОВІ СЛОВА: ефективність управління запасами, інформаційна система, система управління, методи оцінки, фактори, великі дані (Big Data).

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STEWART PLATFORM MULTIDIMENSIONAL TRACKING CONTROL SYSTEM SYNTHESIS

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ABSTRACT

Context. Creating guaranteed competitive motion control systems for complex multidimensional moving objects, including unstable ones, that operate under random controlled and uncontrolled disturbing factors, with minimal design costs, is one of the main requirements for achieving success in this class devices market. Additionally, to meet modern demands for the accuracy of motion control processes along a specified or programmed trajectory, it is essential to synthesize an optimal control system based on experimental data obtained under conditions closely approximating the real operating mode of the test object.

Objective. The research presented in this article aims to synthesize an optimal tracking control system for the Stewart platform's working surface motion, taking into account its multidimensional dynamic model.

Method. The article employs a method of a multidimensional tracking control system structural transformation into an equivalent stabilization system for the motion of a multidimensional control object. It also utilizes an algorithm for synthesizing optimal stabilization systems for dynamic objects, whether stable or not, under stationary random external disturbances. The justified algorithm for synthesizing optimal stochastic stabilization systems is constructed using operations such as addition and multiplication of polynomial and fractional-rational matrices, Wiener factorization, Wiener separation of fractional-rational matrices, and the calculation of dispersion integrals.

Results. As a result of the conducted research, the problem of defining the concept of analytical design for a Stewart platform's optimal motion control system has been formalized. The results include the derived transformation equations from the tracking control system to the equivalent stabilization system of the Stewart platform's working surface motion. Furthermore, the structure and parameters of the main controller transfer function matrix for of this control system have been determined.

Conclusions. The justified use of the analytical design concept for the Stewart platform's working surface optimal motion control system formalizes and significantly simplifies the solution to the problem of synthesizing complex dynamic systems, applying the developed technology presented in [1]. The obtained structure and parameters of the Stewart platform's working surface motion control system main controller, which is divided into three components W_1, W_2, and W_3, improve the tracking quality of the program signal vector, account for the cross-connections within the Stewart platform, and increase the accuracy of executing the specified trajectory by increasing the degrees of freedom in choosing the controller structure.

KEYWORDS: synthesis, transfer function matrix, tracking control system, quality functional, Stewart platform.

ABBREVIATIONS

MFD is a method of matrix fraction description;

WS is a working surface.

NOMENCLATURE

C is a non-negative definite polynomial weight matrix of size $m \times m$, which bounds the variance of the control signal u;

E_{2n} is the $2n \times n$ unit matrix;

G_0+G_+ is a stable fractional-rational matrix, which is the stable part of the result of the separation of the matrix G;

G_n is a gain coefficient of the disturbance spectral density matrix in the controlled object $S^{/}_{\psi_{ob}\psi_{ob}}$;

K_g is a gain coefficient of the feedback matrix characterizing the dynamics of the object P_0^{-1};

M_1, M_0 is an (extended) polynomial matrix of dimensions 2n×m and n×m, respectively, that determines the sensitivity of the object to changes in control signals;

m is the number of signals at the output of the control system;

n is the local system inputs number;

$O_{m\times n}$ is a zero matrix of size $m \times n$;

P_1, P_0 is an (extended) polynomial matrix of dimensions $2n \times 2n$ and $n \times n$, respectively, that characterizes the dynamics of the control object;

R is a positively definite polynomial weight matrix of size $n \times n$, which determines the influence of the stabilization error variance on the criterion e;

r_0 is a vector of program signals;

$S^{/}_{r_0 r_0}$ is a transposed spectral density matrix of the vector r_0;

$S^{/}_{uu}$ is a transposed spectral density matrix of control signal deviations;

$S^{/}_{x_{\varepsilon1} x_{\varepsilon1}}$ is a transposed spectral density matrix of the vector $x_{\varepsilon 1}$ at the output of the extended control object;

$S^{/}_{\psi_{ob}\psi_{ob}}$ is a transposedmatrix of spectral densities of the disturbing influence;

$S^{/}_{\xi_0\xi_0}$ is a transposed spectral density matrix of the extended disturbance vector ξ_0;

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$S^{/}_{\varphi_0\psi}$ is a transposed mutual spectral density matrix between vectors φ_0 and ψ;

T_0+T_+ is a stable fractional-rational matrix, which is the stable part of the result of the separation of the matrix T;

u is an m-dimensional vector of control signals;

W_0, W_1, W_2, W_3 are transfer function matrices of the main controller and its components;

x_1 is a vector of signals at the output of the control system;

x_ε is extended vector of reactions;

z_1, - z_{11} are auxiliary transfer functions;

z_{22}, z_{21} are fractional rational matrices;

Φ is a block matrix of transfer functions of size $n\times(n+m)$;

α is a measurement's noise variance coefficient, values: α=0.0018 rad^2;

ε_x is a tracking error;

φ_1, φ_r are vectors of measurement noise;

ψ_{ob} is a vector of centred stationary random disturbances in the control object.

INTRODUCTION

Research results on the methods of designing control systems for mechanisms with a parallel structure based on the Stewart platform [2], taking into account the principles of automatic control theory, have determined that regardless of the application area, all the Stewart platform working surface (WS) motion control systems are multidimensional closed-loop control systems operating under the influence of random disturbances.

In the article [3], the Stewart platform dynamics model is identified and its transfer function, as well as the transfer function of the shaping filter, is determined. It has been determined that the considered mechanism is a multidimensional stable mechanical filter for both control signals and disturbances in the working area of the mechanism. Analysis of the Stewart platform dynamics' model identification results shows that the primary influence on the motion of the moving platform center of mass is the change in control inputs. However, neglecting the impact of disturbances reduces the positioning accuracy of the platform. Therefore, for the synthesis of the control system, methods should be applied that allow for determining the structure and parameters of the multidimensional controller, taking such influences into account.

Given the modern requirements for the accuracy of motion control processes of a moving object along a specified or programmed trajectory, it is necessary to synthesize the optimal structure and parameters of the object's control system, taking into account both real controllable and uncontrollable stochastic disturbing factors [4]. Also, in the process of synthesizing the optimal controller structure, it is necessary to evaluate and consider multidimensional dynamic models of the object itself, its basic parts, as well as the controllable and uncontrollable disturbing factors that affect the object in its real motion.

This work object of study is a Stewart platform's working surface motion multidimensional tracking control system. The Stewart platform is a spatial mechanism with a parallel kinematic structure, consisting of six identical kinematic chains (actuators) [5]. Such mechanisms include processing centers (machines), coordinate measuring centers, vibration platforms (testing rigs), motion simulators, and stabilization platforms. The Stewart platform has six degrees of freedom for the motion of its moving platform. By programmatically adjusting the lengths of the Stewart platform actuators, it is possible to control the position of the moving base, move it in vertical and horizontal directions, and rotate it in three planes.

The subject of study is the algorithm for converting the tracking system into an equivalent stabilization system, as well as the algorithm for synthesizing the Stewart platform's working surface motion control system.

The purpose of the work is to obtain the structure and parameters of an optimal controller for the Stewart platform's working surface motion control system, using a justified multidimensional objects optimal stochastic sta-bilization systems synthesizing algorithm.

1 PROBLEM STATEMENT

As a result of the conducted research and the structural schemes analysis of Stewart platform WS motion control system when used for various types of technological tasks such as positioning, stabilization, motion simulators of moving objects, etc. [5], and taking into account the principles of automatic control theory, it has been established that regardless of the application area, all motion control systems of the Stewart platform WS can be classified as multidimensional dual-loop tracking systems (Fig. 1) [2].

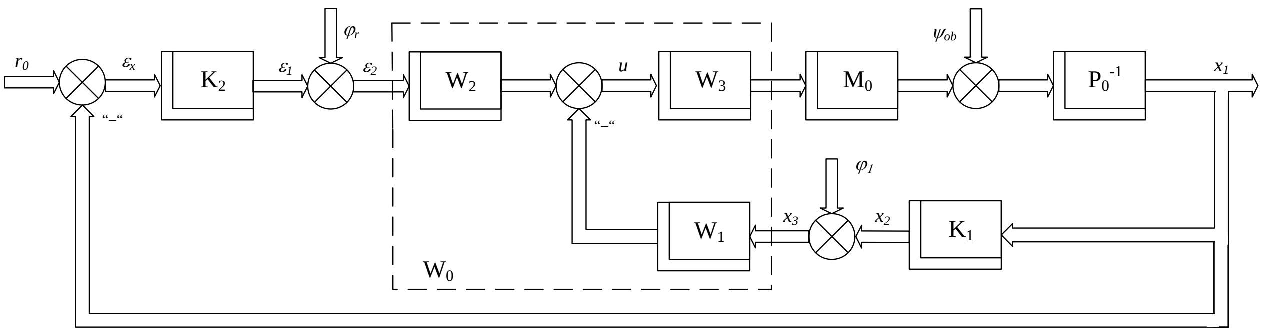

Figure 1 – Structural diagram of a multidimensional dual-loop tracking control system

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We will also consider that the vector of output coordinates x_1 is fully measured using a system of imperfect sensors, whose dynamics are determined by the transfer matrix K_1. At the output of the sensors, there is an n-dimensional vector of centered stationary random noises φ_1, with a fractional-rational matrix spectral density $S_{\varphi_1\varphi_1}$. The system input is an n-dimensional vector of the motion program signal r_0. The program signal setter is described by the transfer function matrix K_2 of size $n\times n$. The stationary random noise of the program signal setter is characterized by the n-dimensional vector φ_r.

The study of research results, which are given in the sources [1, 6–8], made it possible to set the task of defining the Stewart platform WS optimal motion control system analytical design concept.The mentioned concept involves transforming the structural diagram in Fig. 1 into an equivalent structural diagram of a multidimensional stabilization system [6], taking into account the rules of structural diagrams and linear systems transformation [7]. This consolidation formalizes and significantly simplifies the solution of synthesizing complex dynamic systems, such as the Stewart platform's WS motion control system, using the developed technology presented in [1]. This technology utilizes an algorithm for synthesizing optimal systems for stochastic stabilization of motion in multidimensional controlled objects, which is robust even in the presence of stationary random external disturbances. It ensures enhanced reliability in computation results, combining the simplicity of computational algorithms with the capabilities and physical transparency of algorithms described in the monograph [6].

2 REVIEW OF THE LITERATURE

The technologies for synthesizing optimal linear time-invariant multidimensional control systems in the frequency domain [6–10] review has shown that the fundamental creating such systems method can be considered as the synthesizing optimal multidimensional stabilization systems presented in [8] method. It is based on the the Frobenius formula for polynomial matrix inversion use and involves complex computations in forming special-purpose polynomial matrices. All of this limits the effectiveness of applying the algorithms from [8] to solve the synthesis task, especially as the order and dimensions of the controlled object increase. At the same time, this monograph has proven that the structure and parameters of these service matrices do not affect the choice of the optimal regulator and the effectiveness of its use in the system; they only determine the course and complexity of the computational synthesis processes.

In the monograph [9], a new procedure for determining the aforementioned service matrices is justified based on the factorization of a properly constructed block polynomial matrix. It has allowed the author to significantly simplify the basic synthesis algorithm. At the same time, the relationships obtained in [9] allow for the synthesis of an optimal multidimensional stabilization system designed to operate under random disturbances in the form of a white noise vector and with ideal measurement of the output coordinates of the object, such as the Stewart platform.

In the monograph [6], a new method for synthesizing optimal multidimensional stabilization systems for dynamic objects, including unstable ones, is justified. This method is designed to operate under stationary random external disturbances with "non-ideal" measurements of the object's output coordinates. The algorithms based on this method involve selecting special-purpose polynomial matrices from physical considerations, which significantly simplifies their formation process. At the same time, repeated application of this method for creating stabilization systems has shown that as the dimensionality of the controlled object increases, problems of catastrophic loss of computational accuracy arise when performing computer calculations with limited bit-length precision.

3 MATERIALS AND METHODS

The synthesizing an optimal tracking control system for the Stewart platform's WS motion, as a multidimensional controlled object, task is formulated as follows. Suppose we have an n-dimensional linear controlled object (Fig. 1), whose motion is described by a system of ordinary differential equations, represented under zero initial conditions in the Laplace-transformed form:

$$P_0 x_1 = M_0 u + \psi_{ob} . \quad (1)$$

Supplement the object equation (1) with the error equation:

$$\varepsilon_x = r_0 - x_1 ,$$

so we can write the following system of equations:

$$\begin{cases} P_0 x_1 = M_0 u + \psi_{ob} \\ \varepsilon_x = r_0 - x_1 \end{cases} ,$$

or for better understanding, let's rewrite this system of equations as follows:

$$\begin{cases} P_0 x_1 + O_n \varepsilon_x = M_0 u + \psi_{ob} \\ E_n x_1 + E_n \varepsilon_x = O_n + r_0 \end{cases} . \quad (2)$$

Write the system of equations (2) in vector-matrix form:

$$\begin{bmatrix} P_0 & O_n \\ E_n & E_n \end{bmatrix} \begin{bmatrix} x_1 \\ \varepsilon_x \end{bmatrix} = \begin{bmatrix} M_0 \\ O_{n\times m} \end{bmatrix} u + \begin{bmatrix} \psi_{ob} \\ r_0 \end{bmatrix},$$

introduce new notations:

$$P_1 = \begin{bmatrix} P_0 & O_n \\ E_n & E_n \end{bmatrix}, \; M_1 = \begin{bmatrix} M_0 \\ O_{n\times m} \end{bmatrix}, \; \psi_r = \begin{bmatrix} \psi_{ob} \\ r_0 \end{bmatrix}, \quad (3)$$

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$$x_\varepsilon = \begin{bmatrix} x_1 \\ \varepsilon_x \end{bmatrix},$$

Given the notation (3), equation (1) can be written as follows:

$$P_1 x_\varepsilon = M_1 u + \psi_r \,, \tag{4}$$

As seen in Fig. 1, the input to the sensors K_1 and K_2 are the output coordinate vector of the controlled object x_1 and the tracking system error ε, respectively, while the output of the sensors K_1 and K_2 yield the vectors x_2 and ε_1. Then, the following equation can be written:

$$\begin{bmatrix} x_2 \\ \varepsilon_1 \end{bmatrix} = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix} \begin{bmatrix} x_1 \\ \varepsilon_x \end{bmatrix}, \tag{5}$$

introduce the notation:

$$K_0 = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix},\; x_{\varepsilon_1} = \begin{bmatrix} x_2 \\ \varepsilon_1 \end{bmatrix}. \tag{6}$$

The sensors K_1 and K_2 have noises φ_1 and φ_r, which are multidimensional stationary-centered random processes with known spectral density matrices and cross-spectral densities. As seen in Fig. 1, the vectors x_3 and ε_2 act at the input of the regulator W_0 of the tracking system, so the following equation can be written:

$$\begin{bmatrix} x_3 \\ \varepsilon_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ \varepsilon_1 \end{bmatrix} + \begin{bmatrix} \varphi_1 \\ \varphi_r \end{bmatrix}, \tag{7}$$

introduce the notation:

$$x_{\varepsilon_2} = \begin{bmatrix} x_3 \\ \varepsilon_2 \end{bmatrix},\; \varphi_0 = \begin{bmatrix} \varphi_1 \\ \varphi_r \end{bmatrix}. \tag{8}$$

Taking into account equation (5) and notation (6–8), we obtain:

$$x_{\varepsilon_2} = K_0 x_\varepsilon + \varphi_0 \,.$$

According to the block diagram in Fig. 1, the equation of the control signal u can be defined as follows:

$$u = W_3\left(-W_1 x_3 + W_2 \varepsilon_2\right),$$

and in matrix form

$$u = W_3\left[-W_1 \quad W_2\right] \begin{bmatrix} x_3 \\ \varepsilon_2 \end{bmatrix},$$

where W_0 is the transfer function of the controller of the double-loop tracking system:

$$W_0 = W_3\left[-W_1 \quad W_2\right]. \tag{9}$$

Then

$$u = W_0\left(K_0 x_\varepsilon + \varphi_0\right). \tag{10}$$

Therefore, the two-loop tracking system (Fig. 1) is structurally equivalent to the stabilization system depicted in Fig. 2, described by the equations of the object (4) and the controller (10).

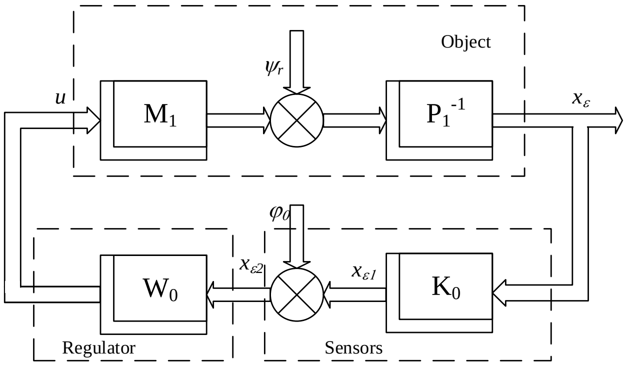

Figure 2 – Structural diagram of a multi-dimensional stabilization system

At the first stage of transformations, the structural diagram (Fig. 2) is reduced to the output x_{ε_1} of the sensors K_0 (Fig. 3), and the resulting system of differential equations is equivalent to the relationships (1):

$$P x_{\varepsilon_1} = M u + \psi \,, \tag{11}$$

in which the following notations are adopted

$$P = K_{10} P_1 K_0^{-1},\; M = K_{10} M_1,\; x_{\varepsilon_1} = K_0 x_\varepsilon,\; \psi = K_{10} \psi_r \,. \tag{12}$$

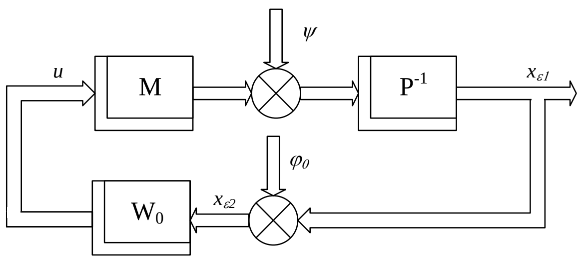

Figure 3 – Result of the structural transformations first stage

To determine the polynomial matrix K_{10} with the minimum possible order of elements, it is proposed to use a combination of algorithms for left-sided pole removal [12] and MFD decomposition [10] of the fractional-rational matrix K_0^{-1} and the product of matrices $P_1 K_0^{-1}$.

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In this process, the matrix K_{10} should be found as a result of the MFD decomposition [10] of the following product:

$$K_{10}^{-1}P = P_1 K_{20}^{-1},$$

where K_{20} is the result of the left-side removal of the poles of the sensor transfer function matrix [12]

$$K_{20}^{-1}K_2 = K_0,$$

and between the determinants of polynomial matrices K_{10} and K_{20} there is an identity

$$|K_{10}| = |K_{20}|,$$

which is a consequence of the MFD decomposition of fractional-rational matrices.

In the second stage, the structural diagram (Fig. 3) is transformed into a standard form (Fig. 4), where the input of the stabilization system is affected by an extended disturbance vector ξ

$$\xi = (E_n, P)\xi_0, \quad (13)$$

where the vector ξ_0 is the result of the vertical concatenation of the vectors ψ and φ_0

$$\xi_0 = \begin{bmatrix} \psi \\ \varphi_0 \end{bmatrix}, \quad (14)$$

a vector x_{ε_2} acts as the output of the system.

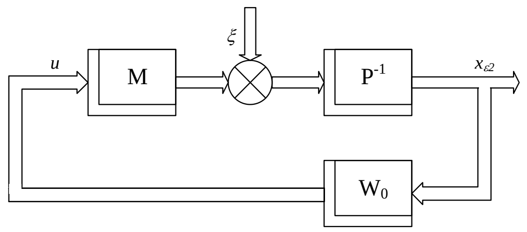

Figure 4 – Structural diagram of a typical stabilization system

By analogy with [6], the relationship between the vectors ξ_0 and x_ε is defined as follows:

$$x_{\varepsilon_2} = K_0^{-1}\left[F_{x_{\varepsilon_2}}^{\xi}(E_{2n}, P) - (O_{2n}, E_{2n})\right]\xi_0, \quad (15)$$

where $F_{x_{\varepsilon_2}}^{\xi}$ is the matrix transfer function of the closed "object + regulator" system from the extended disturbance vector ξ to the output signal vector x_{ε_2}. The control signal vector u in the closed system also depends on the extended disturbance vector ξ

$$u = F_u^{\xi}(E_{2n}, P)\xi_0, \quad (16)$$

where F_u^{ξ} is the matrix transfer function of the closed "object + regulator" system from the extended disturbance vector ξ to the control vector u.

In works [6, 8], based on equation (11), it has been proven that there is a relationship between matrices F_u^{ξ} and $F_{x_{\varepsilon_2}}^{\xi}$, which is characterized by the following relation:

$$PF_{x_{\varepsilon_2}}^{\xi} - MF_u^{\xi} = E_{2n}. \quad (17)$$

Additionally, it has been demonstrated that the structure and parameters of these matrices depend on the matrix of transfer functions of the regulator W_0:

$$F_u^{\xi} = W_0(P - MW_0)^{-1}, \quad (18)$$

$$F_{x_{\varepsilon_2}}^{\xi} = (P - MW_0)^{-1}. \quad (19)$$

Thus, the structural transformations (Fig. 2–4) and equations (15), and (16) reduce the task of synthesizing an optimal stabilization system to the following: it is necessary to determine the structure and parameters of the regulator W_0 transfer function matrix by known polynomial and fractional-rational matrices M_1, P_1, K_0, $S_{\psi_{ob}\psi_{ob}}$, and $S_{\varphi_1\varphi_1}$. The inclusion of the regulator W_0 transfer function in the feedback circle to the control object ensures the stability of the stabilization system (Fig. 2) and delivers a minimum to the following quality criterion:

$$e = \left\langle x_{\varepsilon_1}^{/} R x_{\varepsilon_1} \right\rangle + \left\langle u^{/} C u \right\rangle. \quad (20)$$

By substituting definitions (5) and (6) into the quality criterion of the stabilization system (20), we determine the functional of the quality criterion for the two-loop tracking system as follows:

$$e = \left\langle x_\varepsilon^{/} (K_0^{-1})^{/} \begin{bmatrix} O_n \\ E_n \end{bmatrix} R [O_n, E_n] K_0^{-1} x_\varepsilon \right\rangle + \left\langle u^{/} C u \right\rangle, \quad (21)$$

introduce the notation

$$R_1 = (K_0^{-1})^{/} \begin{bmatrix} O_n \\ E_n \end{bmatrix} R [O_n, E_n] (K_0^{-1}).$$

Unlike in the stabilization system where R is a coefficient, in the tracking system, R_1 equals a matrix 2×2:

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$$R_1 = \begin{bmatrix} O_n & O_n \\ O_n & K_{2*}^{-1} R K_2 \end{bmatrix}. \qquad (22)$$

The task of synthesizing the regulator in the tracking system is to ensure, the first, the stability of the closed-loop tracking system and, the second, minimum of the system functional (21) by selecting the optimal structure of the regulator W_0.

To solve this problem, rewrite the functional (20) in the frequency domain:

$$e = \frac{1}{j} \int_{-j\infty}^{j\infty} tr\left(S'_{x_{\varepsilon1} x_{\varepsilon1}} R_1 + S'_{uu} C \right) ds. \qquad (23)$$

Define the matrix of varied transfer functions Φ as follows

$$F_u^{\xi} = z_{22}\Phi + z_{21}, \qquad (24)$$

where

$$z_{22} = \left(B + AP^{-1}M \right)^{-1}, \; z_{21} = -z_{22} A P^{-1}, \qquad (25)$$

A and B are polynomial matrices found as a result of representing the auxiliary block matrix H:

$$H = \begin{bmatrix} O_{2n} & P & -M \\ P_* & -R & O_{2n\times m} \\ -M_* & O_{m\times 2n} & -C \end{bmatrix}, \qquad (26)$$

in the form of the product of two factors (block polynomial matrices) V and Σ:

$$H = V_* \Sigma V, \qquad (27)$$

where

$$V = \begin{bmatrix} E_{2n} & -S & N \\ O_n & P & -M \\ O_{m\times 2n} & A & B \end{bmatrix}, \quad \Sigma = \begin{bmatrix} O_{2n} & E_{2n} & O_{2n\times m} \\ E_n & O_{2n} & O_{2n\times m} \\ O_{m\times 2n} & O_{m\times 2n} & -E_m \end{bmatrix}, \qquad (28)$$

provided that the determinant |V| is a Hurwitz polynomial.

The algorithm for factorizing matrix (27) was firstly proposed and detailed in [9]. Substituting expressions (26) and (28) into equation (27) establishes the existence of the following relationships:

$$\begin{aligned} &P_* S + S_* P + A_* A = R, \\ &M_* S + N_* P - B_* A = O_{m\times 2n}, \\ &P_* N + S_* M - A_* B = O_{2n\times m}, \\ &M_* N + N_* M + B_* B = C. \end{aligned} \qquad (29)$$

In this case, the performance criterion (23) with equations (13–17) and (24) transforms into the functional:

$$\begin{aligned} e = \frac{1}{j} \int_{-j\infty}^{j\infty} tr\Bigg\{ \Bigg[& \left[\begin{pmatrix} E_n \\ P_* \end{pmatrix} z_{21*} M_* P_*^{-1} RG + \begin{pmatrix} E_n \\ P_* \end{pmatrix} P_*^{-1} \times \right. \\ & \times RG \Big] S'_{\xi_0\xi_0} + \Phi_* z_{22*} M_* P_*^{-1} RG S'_{\xi_0\xi_0} \begin{pmatrix} E_n \\ P_* \end{pmatrix} - \\ & - \begin{pmatrix} O_n \\ E_n \end{pmatrix} RG S'_{\xi_0\xi_0} + \left[z_{21*} C z_{21} + z_{21*} C z_{22} \Phi + \Phi_* \times \right. \\ & \times z_{22*} C z_{21} + \Phi_* z_{22*} C z_{22} \Phi \Big] (E_n, P) S'_{\xi_0\xi_0} \begin{pmatrix} E_n \\ P_* \end{pmatrix} \Bigg\} ds, \end{aligned} \qquad (30)$$

where "*" is the sign of the Hermitian matrix conjugation [13], G is a fractional-rational matrix equal to

$$G = P^{-1} M z_{21} (E_n, P) + P^{-1} M z_{22} \Phi (E_n, P) + + P^{-1}(E_n, P) - (O_n, E_n).$$

The matrix $S'_{\xi_0\xi_0}$ is defined as the result of applying the Wiener-Khinchin theorem to the vector (14) in the form:

$$S'_{\xi_0\xi_0} = \begin{bmatrix} S'_{\psi\psi} & S'_{\varphi_0\psi} \\ S'_{\psi\varphi_0} & S'_{\varphi_0\varphi_0} \end{bmatrix}, \qquad (31)$$

where matrix $S'_{\psi\psi}$ is the transposed matrix of spectral densities of the equivalent disturbances vector, which, considering expression (12), is equal to:

$$S'_{\psi\psi} = K_{10} \cdot S'_{\psi_r \psi_r} \cdot K_{10*}, \qquad (32)$$

$$S'_{\varphi_0\psi} = K_{10} \cdot S'_{\varphi_1\psi_r}. \qquad (33)$$

The search for the algorithm to determine the structure and parameters of the transfer function matrix W, as in [6, 8, 9], can be accomplished by minimizing the functional (30) on the class of robust and physically realizable variable matrices Φ using the Wiener-Kolmogorov procedure. According to this procedure, the first variation of the functional (30) has been found:

$$\delta e = \frac{1}{j} \int_{-j\infty}^{j\infty} tr\left[\delta\Phi_* \frac{\partial}{\partial \Phi_*} tr(*) + \frac{\partial}{\partial \Phi} tr(*)_* \delta\Phi \right] ds, \qquad (34)$$

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$$\frac{\partial}{\partial \Phi_*} tr(*) = z_{22*}\left(M_* P_*^{-1} R P^{-1} M + C\right) z_{22} \Phi \times$$
$$\times (E_n, P) S'_{\xi_0\xi_0} \begin{pmatrix} E_n \\ P_* \end{pmatrix} + z_{22*}\left(M_* P_*^{-1} R P^{-1} M z_{21} + \right.$$
$$\left. + M_* P_*^{-1} R P^{-1} + C z_{21}\right)(E_n, P) S'_{\xi_0\xi_0} \times \tag{35}$$
$$\times \begin{pmatrix} E_n \\ P_* \end{pmatrix} - z_{22*} M_* P_*^{-1} R (O_n, E_n) S'_{\xi_0\xi_0} \begin{pmatrix} E_n \\ P_* \end{pmatrix}.$$

Define the matrix D as the result of the left-sided factorization [11] of generalized disturbances spectral density's transpose matrix.

$$DD_* = (E_n, P) S'_{\xi_0\xi_0} \begin{pmatrix} E_n \\ P_* \end{pmatrix}. \tag{36}$$

Assume that the fractional-rational matrix T equals:

$$T = z_{22*}\left(M_* P_*^{-1} R P^{-1} M z_{21} + M_* P_*^{-1} R P^{-1} + C z_{21}\right) D, \tag{37}$$

and the matrix G:

$$G = -z_{22*} M_* P_*^{-1} R \left(S'_{\psi\varphi_0} + S'_{\varphi_0\varphi_0} P_*\right) D_*^{-1}. \tag{38}$$

Since the relationships (29) hold, the expression (37) is reduced to the form:

$$T = z_{22*}\left(M_* P_*^{-1} S_* - N_*\right) D,$$

and the partial derivative (35) is simplified and represented as

$$\frac{\partial}{\partial \Phi_*} tr(*) = \Phi DD_* + TD_* - GD_*.$$

Thus, the first variation of the quality functional (34) becomes equal to:

$$\delta e = \frac{1}{j} \int_{-j\infty}^{j\infty} tr\left[\delta\Phi_* \left(\Phi DD_* + TD_* - GD_*\right) + \right.$$
$$\left. + \left(DD_* \Phi_* + DT_* - DG_*\right) \delta\Phi\right] ds. \tag{39}$$

As seen from the monograph [6], the matrix of variable functions Φ, which meets the conditions of stability and physical realizability and minimizes the functional (30), considering expression (39), should be determined based on the following relationship:

$$\Phi = -\left(T_0 + T_+ + G_0 + G_+\right) D^{-1}. \tag{40}$$

Substituting the result (40) into expression (24) and solving equation (18) for the regulator's transfer function matrix, taking into account relationship (25), allows us to determine that:

$$W_0 = (B + \Phi M)^{-1}(-A + \Phi P). \tag{41}$$

4 EXPERIMENTS

The initial data for synthesizing the optimal structure of the Stewart platform's WS motion two-loop tracking control systems consists of its dynamic models, as a control object, as well as the spectral density of the acting disturbance, which were determined based on the results of field tests under conditions close to the real operating mode of the experimental sample of the Stewart platform, using special algorithms [3]. Thus, the dynamics of the Stewart platform (Fig. 1) are described by the matrices:

$$P_0 = \begin{bmatrix} z_2 & 0 & 0 \\ 0 & z_2 & 0 \\ 0 & 0 & z_2 \end{bmatrix}, \tag{42}$$

where $z_1 = \left(s^2 + 0.63s + 0.15\right)\left(s^2 + 2s + 1.09\right)$, $z_2 = \left(s^2 + 0.11s + 0.04\right) z_1$,

$$M_0 = \begin{bmatrix} 0.013(s+5.4)(s+0.83)(s+0.15)\left(s^2+0.3s+0.067\right) & -0.016(s-2.1)(s+0.14)(s-0.027)\left(s^2+1.89s+1\right) \\ 0.01(s+2.1)\left(s^2+0.22s+0.03\right)\left(s^2+1.35s+0.83\right) & -0.004(s+9.3)\left(s^2+1.95s+1\right)\left(s^2+0.067s+0.09\right) \\ 0.05(s+0.96)\left(s^2+0.5s+0.14\right)\left(s^2-0.018s+0.2\right) & 0.006(s+0.19)\left(s^2+1.4s+0.54\right)\left(s^2+1.23s+4.09\right) \end{bmatrix}$$
$$\begin{matrix} -0.008(s-2.1)(s+0.76)(s+0.19)\left(s^2+0.24s+0.085\right) \\ 0.004(s+1.95)\left(s^2+0.22s+0.055\right)\left(s^2+1.06s+0.67\right) \\ 0.025(s+0.94)\left(s^2-0.2s+0.067\right)\left(s^2+0.59s+0.17\right) \end{matrix} \Bigg], \tag{43}$$

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the spectral density of the acting disturbance $S'_{\psi_0\psi_0}$:

$$S'_{\psi_{ob}\psi_{ob}} = 10^{-4} z_4 \begin{bmatrix} 9 & 5.3 & 3.2 \\ 5.3 & 9 & 6.7 \\ 3.2 & 6.7 & 34.4 \end{bmatrix}, \quad (44)$$

where $z_3 = (s+0.45)(s+0.55)$,

$$z_4 = \left| \frac{(s^2+0.1s+0.04)(s^2+0.6s+0.15)(s^2+2s+1)}{z_3} \right|^2 .$$

Since the measurement of the output coordinate vector x_1 and the program signal vector r_0 is performed by inertialess measuring devices, which according to their technical specifications are proportional elements with a transfer coefficient equal to 1, the following equations are satisfied:

$$K_{10} = K_{20} = E_{3\times3}, K_0 = K_1 = K_2 = E_{3\times3},$$

according to the definitions (12) and (32), (33) following equations take place

$$P = P_1,\ M = M_1,\ S'_{\psi\psi} = S'_{\psi_r\psi_r},\ S'_{\varphi_0\psi} = S'_{\varphi_0\psi_r},$$
$$x_2 = x_1,\ \psi = \psi_r . \quad (45)$$

To find the auxiliary matrix *H*, it is necessary to determine the polynomial weight matrices R_1, which defines the impact of stabilization error variance on the criterion value (20), and *C*, which limits the variance of the control signal *u*.

Based on the methodology for determining weight matrices presented in the works [14], we obtain the polynomial weight matrix R_1, according (22):

$$R_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.16 & -0.002 & -0.06 \\ 0 & 0 & 0 & -0.002 & 0.24 & -0.165 \\ 0 & 0 & 0 & -0.06 & -0.165 & 1.17 \end{bmatrix}, \quad (46)$$

the polynomial weight matrix *C* is equal to:

$$C = \begin{bmatrix} 0.01 & 0 & 0 \\ 0 & 0.01 & 0 \\ 0 & 0 & 0.01 \end{bmatrix}. \quad (47)$$

Substituting matrices (42), (43), (46), (47) into expression (26) allows us to determine the auxiliary polynomial matrix *H*. Factorization of this matrix based on algorithm [9] allowed us to determine the following blocks of the matrix *V* (28), necessary for further synthesis:

$$A = O_{12\times12},\ B = E_{3\times3}, \quad (48)$$

$$S = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0797 & -0.00107 & -0.031519 \\ 0 & 0 & 0 & -0.00107 & 0.11927 & -0.0825 \\ 0 & 0 & 0 & -0.031519 & -0.0825 & 0.58515 \end{bmatrix} \quad (49)$$

$$N = \frac{10^{-3}}{z_5} \left[\begin{matrix} 0.555(s-9.269)(s+0.867)(s+0.00885)(s^2+0.39s+0.083) \\ 2.9(s-0.8)(s+0.337)(s-0.19)(s^2+1.24s+0.39) \\ -27.579(s+0.9399)(s^2+0.5398s+0.1419)(s^2-0.16s+0.22) \\ 0.555(s-9.269)(s+0.867)(s+0.00885)(s^2+0.39s+0.083) \\ 2.9(s-0.8)(s+0.337)(s-0.19)(s^2+1.24s+0.39) \\ -27.579(s+0.9399)(s^2+0.5398s+0.1419)(s^2-0.16s+0.22) \end{matrix} \right.$$
$$\begin{matrix} 1.4946(s-1.419)(s-0.29)(s+0.159)(s^2+1.8s+0.96) \\ 0.93919(s+3.8)(s+2.185)(s+0.2466)(s^2+0.4747s+0.1616) \\ -4.57(s+0.195)(s^2+1.29s+0.5287)(s^2+1.567s+3.496) \\ 1.4946(s-1.419)(s-0.29)(s+0.159)(s^2+1.8s+0.96) \\ 0.93919(s+3.8)(s+2.185)(s+0.2466)(s^2+0.4747s+0.1616) \\ -4.57(s+0.195)(s^2+1.29s+0.5287)(s^2+1.567s+3.496) \end{matrix} \quad (50)$$

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$$\begin{bmatrix} 1.4(s-0.856)(s+0.8166)(s+0.06667)(s^2+0.35s+0.1) \\ 1.5936(s-0.7858)(s^2+0.31s+0.02536)(s^2+1.239s+0.395) \\ -14.688(s+0.918)(s^2-0.256s+0.05877)(s^2+0.5895s+0.16) \\ 1.4(s-0.856)(s+0.8166)(s+0.06667)(s^2+0.35s+0.1) \\ 1.5936(s-0.7858)(s^2+0.31s+0.02536)(s^2+1.239s+0.395) \\ -14.688(s+0.918)(s^2-0.256s+0.05877)(s^2+0.5895s+0.16) \end{bmatrix},$$

where

$$z_5 = \left|s^2+0.113s+0.0439\right|^2 \left|s^2+0.625s+0.15\right|^2 \times$$
$$\times \left|s^2+2.005s+1.087\right|^2 .$$

After substituting matrices (48) into expression (25), the fractional-rational matrices z_{22} and z_{21} are found to be:

$$z_{21} = O_{12\times12}, \; z_{22} = E_{3\times3}. \quad (51)$$

To determine the matrix $S'_{\xi_0\xi_0}$ (31), we consider definition (45), as well as the fact that the extended vector of output signals ψ and the extended vector of measurement device noises φ_0 are not correlated with each other. Thus,

$$S'_{\varphi_0\psi} = S'_{\varphi_1\psi_{ob}} = O_{3\times3}.$$

Based on this, we can determine:

$$S'_{\xi_0\xi_0} = \begin{bmatrix} Q_n & O_{3\times3} & O_{3\times3} & O_{3\times3} \\ O_{3\times3} & DS_{rr} & O_{3\times3} & O_{3\times3} \\ O_{3\times3} & O_{3\times3} & R_n & O_{3\times3} \\ O_{3\times3} & O_{3\times3} & O_{3\times3} & gE \end{bmatrix},$$

where

$$S'_{\psi\psi} = \begin{bmatrix} Q_n & O_{3\times3} \\ O_{3\times3} & DS_{rr} \end{bmatrix},$$

DS_{rr} – the of amplification coefficients matrix of the input signal r_0 spectral density matrix, taken from [3], Q_n – the weighted covariance matrix of the input signals ψ extended vector, disturbance ψ_{ob}, and program signal r_0.

According to [7], the weighted covariance matrix Q_n is equal to:

$$Q_n = K_g^{-1}(G_n - \alpha\Omega)K_g^{-1},$$

$$Q_n = 10^{-5}\begin{bmatrix} 0.0665 & 0.0441 & 0.0266 \\ 0.0441 & 0.0646 & 0.0555 \\ 0.0266 & 0.0555 & 0.2594 \end{bmatrix}.$$

$$S'_{\varphi_0\varphi_0} = \begin{bmatrix} R_n & O_{3\times3} \\ O_{3\times3} & gE \end{bmatrix},$$

where gE – the matrix, which is determined according to recommendations [14], as a quantity approaching zero, R_n – the weighted covariance matrix of the measurement's noises extended vector $R_n = \langle \varphi_0 \varphi_0^{/} \rangle$.

According to (8), the measurement's noises extended vector φ_0 consists of the program signal measurement's noises φ_r, whose values approach zero, and of the output signal measurement's noises φ_1, whose values are determined by the root-mean-square deviation of the feedback sensor values. As the feedback sensor, an inertial navigation system [16] is used, with the following root-mean-square deviation values along the axes:

$$\varphi_1 = \frac{\pi}{180}\begin{bmatrix} 0.769 & 0.847 & 1.344 \end{bmatrix}^{/}.$$

Thus, R_n is equal:

$$R_n = \begin{bmatrix} 0.0018 & 0 & 0 \\ 0 & 0.0022 & 0 \\ 0 & 0 & 0.0056 \end{bmatrix}.$$

5 RESULTS

Based on the above experimental data, the product DD* is obtained using expression (36). Define the matrix D as the result of the left-sided factorization [11] product DD*:

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$$D=\begin{bmatrix} 0.042426\cdot z_8 & 0.0032097(s+0.39)z_6 & 0.00063363(s+0.45)z_6 & 0.00078229(s+0.3158)z_7 & 0.00048716(s+0.41)z_6 & -0.0005479(s+0.1556)z_7 \\ 0.0035306(s+0.39)z_6 & 0.046669z_8 & 0.0019254(s+0.418)z_6 & 0.0002854(s+0.39)z_6 & 0.0016987(s+0.3)\cdot z_7 & 0.00068386(s+0.412)z_6 \\ 0.0011156(s+0.45)z_6 & 0.0030819(s+0.418)z_6 & 0.074699z_8 & 9.018\cdot 10^{-5}(s+0.45)z_6 & 0.00058573(s+0.42)z_6 & 0.007968(s+0.334)z_7 \\ -0.042426 & 0 & 0 & 0.52486 & 0 & 0 \\ 0 & -0.046669 & 0 & 0.042654 & 0.23899 & 0 \\ 0 & 0 & -0.074699 & 0.18619 & -0.013884 & 0.1671 \end{bmatrix}, \quad (52)$$

where $z_6=(s^2+0.5689s+0.19)(s^2+2s+1.09)$,
$z_7=(s^2+0.55s+0.16)(s^2+2s+1.09)$,
$z_8=(s^2+0.69s+0.166)(s^2+2s+1.09)\times$
$\times(s^2+0.27s+0.1)$.

Taking into account the obtained results (48–52), as well as the fact that the extended vector of output signals ψ and the extended vector of measurement device noises φ_0 are not correlated, we will determine the fractional-rational matrices T and G, which are subject to separation, based on equations (37) and (38). The matrix G has only negative poles, so the result of the separation G_0+G_+ equals O_{3x3}. The result of the T matrix separation is as follows:

$$T_0+T_+=\frac{10^{-4}}{z_9}\begin{bmatrix} 6.187(s+0.178)(s^2+0.5986s+0.15) & 12.18(s+0.089)(s^2+0.605s+0.148) & 43.5(s-0.0249)(s^2+0.61s+0.148) & 0 & 2.286(s+0.085)(s^2+0.61s+0.148) & 18.32(s-0.0277)(s^2+0.625s+0.15) \\ 7.98(s+0.225)(s^2+0.62s+0.156) & 26.64(s+0.114)(s^2+0.617s+0.152) & 160.7(s+0.036)(s^2+0.6186s+0.15) & 0 & 0 & 69.91(s+0.0377)(s^2+0.625s+0.15) \\ 1.3696(s+0.096)(s^2+0.597s+0.146) & 1.578(s-0.0034)(s^2+0.5897s+0.14) & 0.128(s-7.7)(s^2+0.5778s+0.127) & 0 & 0 & -0.217(s+1.786)(s^2+0.625s+0.15) \end{bmatrix},$$

where $z_9=(s^2+0.113s+0.0439)(s^2+0.625s+0.15)$.

Thus, using equation (40) and the results of the separation T_0+T_+, G_0+G_+, the varying matrix Φ can be determined.

So, as a result of applying algorithm (41) using the obtained matrix Φ and definitions (3), (45), and (48), we find the transfer function matrix of the controller for the two-loop tracking system in the form:

$$W_0=\frac{1}{z_{10}}\begin{bmatrix} 854.69(s+1.447)(s^2+8.117s+26.65)(s^2+6.165s+34.87) & 665.55(s+1.674)(s^2+10.1s+46.47)(s^2+4.286s+26.75) \\ 269.13(s+1.49)(s^2+5.712s+14.1)(s^2+8.98s+130.7) & -323.24(s+15.62)(s-3.042)(s+1.579)(s^2+6.54s+29.76) \\ -204.87(s+1.46)(s^2+7.5s+24.4)(s^2+5.03s+137.3) & -347.88(s+1.65)(s^2+3.137s+29.15)(s^2+12.6s+76.73) \end{bmatrix} \quad (53)$$

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$$
\begin{matrix}
906.75(s+0.946)(s^2+10.23s+32.73)(s^2+5.456s+23.9)\\
865.26(s+0.9466)(s^2+10.08s+34.07)(s^2+5.716s+17.9)\\
-798.6(s+0.9462)(s^2+10.12s+33.55)(s^2+6.867s+27.39)
\end{matrix}
$$

$$
\begin{matrix}
-2.0366(s^2+10.4s+33.5)(s^2+5s+21.28)(s^2+7.135s+145.1)/s\\
0.090625(s+58.39)(s-51.5)(s^2+10.4s+34.15)(s^2+4.06s+14.95)/s\\
-9.79(s+11.1)(s-1.9)(s^2+10.46s+33.67)(s^2+5.07s+21.4)/s
\end{matrix}
$$

$$
\begin{matrix}
-7.6496(s^2+7.9s+26.64)(s^2+5.7s+30.76)(s^2+10.14s+62.3)/s\\
6.226(s+13.4)(s-3.6)(s^2+5.9s+20.1)(s^2+7.995s+33.49)/s\\
1.649(s^2+7.318s+25.36)(s^2+7.426s+45)(s^2+11.2s+185.6)/s
\end{matrix} ,
$$

$$
\left.\begin{matrix}
-6.11(s^2+10.88s+33.05)(s^2+4.869s+19.66)(s^2+7.656s+46.29)/s\\
7.8247(s^2+10.89s+30.7)(s^2+4.3s+13)(s^2+8.16s+45.12)/s\\
1.1987(s+10.85)(s+32.6)(s^2+4.79s+18.36)(s^2+9.877s+234.8)/s
\end{matrix}\right]
$$

where $z_{10}=(s+8.538)(s+0.97)(s^2+10.48s+33.15)\times$ $\times(s^2+4.918s+24.3)$.

The structure and parameters of the transfer function matrices of the optimal multidimensional controller (Fig. 1) for the tracking system (9) were determined. According to [11], there exists a pair of matrices W_3 and $[-W1\ W2]$ that form a left coprime factorization of the matrix W_0. Using the methodology from [17], which allows for the computation of the normalized left coprime factorization of a matrix, the components of the transfer function matrices of the optimal multivariable controller W_0 (9) can be written as follows:

$$
W_1=\frac{1}{z_{11}}\left[\begin{matrix}
-854.69(s+1.2)(s^2+6.898s+21.5)(s^2+6.06s+20.6)\\
-269.13(s+0.75)(s^2+9.155s+29.4)(s^2+5.339s+32.76)\\
204.87(s-1.336)(s^2+6.878s+16.39)(s^2+4.865s+14)
\end{matrix}\right.
$$

$$
\begin{matrix}
-665.55(s+2.697)(s^2+4.36s+11)(s^2+7.267s+26.86)\\
323.24(s+0.64)(s^2+7.1s+25.85)(s^2+11.09s+54.87)\\
347.88(s+2.76)(s^2+4.815s+13.1)(s^2+6.59s+23.8)
\end{matrix} , \quad W_2=\frac{1}{s}\begin{bmatrix}
-2.0366 & -7.6496 & -6.11\\
0.09 & 6.226 & -7.8247\\
-9.79 & 1.649 & 1.1987
\end{bmatrix},
$$

$$
\left.\begin{matrix}
-906.75(s+0.9598)(s^2+5.76s+16.37)(s^2+8.309s+33.8)\\
-865.26(s+0.9937)(s^2+6.079s+17.86)(s^2+8.4s+35.2)\\
798.6(s+0.9468)(s^2+5.68s+16)(s^2+8.36s+34.6)
\end{matrix}\right]
$$

$$
W_3=\frac{1}{z_{10}}\left[\begin{matrix}
(s^2+9.43s+32.57)(s^2+5.51s+25.2)(s^2+8.625s+55.26)\\
-0.159\,(s-262.9)(s^2+5.1s+19.39)(s^2+8.919s+33.28)\\
-0.213(s+220.1)(s^2+9.635s+34.4)(s^2+5.7s+24.79)
\end{matrix}\right.
$$

$$
\begin{matrix}
-0.159(s+78.46)(s^2+6.618s+19.46)(s^2+6.37s+41.75)\\
(s+9.99)(s-0.2656)(s^2+5.879s+17.4)(s^2+7.88s+36.98)\\
0.052825(s+25.17)(s^2+6.395s+18.8)(s^2-19.59s+347.5)
\end{matrix} ,
$$

$$
\left.\begin{matrix}
-0.213(s-81.35)(s^2+10.79s+33.96)(s^2+4.8s+20.36)\\
0.052825(s+363.6)(s^2+10.96s+34)(s^2+3.767s+13.1)\\
(s+10.1)(s-0.96)(s^2+10.68s+33.5)(s^2+4.938s+20.8)
\end{matrix}\right]
$$

where
$z_{11}=(s^2+5.65s+15.87)(s^2+7.767s+29.11)\times$ $\times(s^2+8.589s+36.66)$.

The main controller is divided into three components: W_1, W_2 and W_3. This distribution of the controller enhances the tracking quality of the program signal vector and accounts for cross-connections within the Stewart platform. Additionally, it allows for increased precision in following the specified trajectory by increasing the degrees of freedom in selecting the controller structure.

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6 DISCUSSION

The justified transformations (3)–(16) form the basis for developing an information technology to convert the structure of a multidimensional two-loop tracking system into a multidimensional stabilization system. This transformation will enable the assessment of tracking quality and control costs in a two-loop multidimensional tracking system under random and regular influences using standardized approaches for stabilization system analysis.

The developed rules for calculating the transfer function matrices of the controller (41) provide a theoretical basis for defining an information technology for synthesizing an optimal multidimensional two-loop tracking system, which ensures the highest possible tracking accuracy along a random trajectory with an acceptable level of control costs. The main limitation of using the relation (41) is related to the requirement for the stationary and centricity of the multidimensional useful signals and disturbances acting at the system inputs.

The implementation of the obtained transfer function matrices of the controller (Fig. 1) using microprocessor technology requires the representation of the matrix equation as follows:

$$u = W_3 \begin{bmatrix} -W_1 & W_2 \end{bmatrix} \begin{bmatrix} x_3 \\ \varepsilon_2 \end{bmatrix},$$

in the form of a finite-difference equation.

Additionally, the availability of algorithms for calculating the matrix of optimal transfer functions (24) from the extended disturbance vector ξ to the control signal vector u allows for the synthesis of an optimal quadratic criterion (20) neuron-phase regulator.

CONCLUSIONS

The work involved synthesizing the optimal structure and parameters of a multidimensional tracking control system the Stewart platform's WS motion control system, considering a multidimensional dynamic model that includes the object itself, its basic components, controlled and uncontrolled disturbances acting on it in conditions close to real operating modes.

The scientific novelty of the obtained results lies in the application of the tracking system reduction algorithm to an equivalent stabilization system, which allowed for the use of a justified method to synthesize an optimal multidimensional stabilization system for a dynamic object operating under the influence of multidimensional stationary random useful signals, disturbances, and measurement noise.

The practical significance of the obtained results lies in determining the Stewart platform's WS motion control system main controller structure and parameters. Its integration into the feedback loop ensures the stability of the closed-loop control system. The main controller is distributed into three components: W_1, W_2, and W_3, which improves the quality level of tracking the program signals vector and allows for the consideration of cross-couplings within the Stewart platform. It also provides the capability to increase the accuracy of trajectory execution by increasing the number of freedom degrees in the controller structure, as the controller consists of three transfer function elements.

Perspectives for further research. Considering that the stabilization system synthesis algorithm forms the basis for developing any closed-loop control system, it is worthwhile to consider the next step as the development of an information technology for analytical design of optimal multidimensional tracking systems under random influences.

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СИНТЕЗ БАГАТОВИМІРНОЇ СЛІДКУВАЛЬНОЇ СИСТЕМИ КЕРУВАННЯ ПЛАТФОРМИ СТЮАРТА

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АНОТАЦІЯ

Актуальність. Створення гарантовано конкурентоспроможних систем керування рухами складних багатовимірних рухомих об'єктів, у тому числі нестійких, які функціонують в умовах дії випадкових контрольованих та неконтрольованих збурюючих факторів, з мінімальними витратами на проектування є однією з головних вимог досягнення успіху на ринку даного класу пристроїв. Також важливо, для досягнення сучасних вимог до точності процесів керування рухом рухомого об'єкта на заданій або програмованій траєкторії руху необхідно синтезувати оптимальну системи керування на підставі експерементальних даних отриманих в умовах наближених до реального режима функціонування дослідного зразка об'єкту.

Мета роботи. Метою дослідження, результати якого представлені у цій статті, є виконання синтезу оптимальної слідкувальної системи керування рухом робочої поіерхні платформи Стюарта з врахуванням її багатовимірної моделі динаміки.

Метод. У статті використано метод структурного перетворення багатовимірної слідкувальної системи керування до еквівалентної системи стабілізації руху багатовимірних об'єктів керування. Також викорестано алгоритм синтезу оптимальної системи стабілізації динамічних об'єктів, як стійких, так ні, в умовах дії стаціонарних випадкових зовнішніх збурень. Обгрунтований алгоритм синтезу оптимальних стохастичних систем стабілізації, побудований за допомогою операцій додавання, множення поліноміальних та дробово – раціональних матриць, вінеровської факторизації, вінеровської сепарації дробово – раціональних матриць, знаходження дисперсійних інтегралів.

Результати. В результаті проведених досліджень формалізовано задачу визначеня концепції аналітичного конструювання оптимальної системи керування рухом РП платформи Стюарта. Результати включають визначені рівняння перетворення з слідкуючої системи керування до еквівалентної системи стабілізації руху робочої поіерхні платформи Стюарта. Також визначено структуру і параметри матриці передавальних функцій гововного регулятора оптимальної слідкувальної системи керування рухом робочої поіерхні платформи Стюарта.

Висновки. Обгрунтоване використання концепції аналітичного конструювання оптимальної системи керування рухом РП платформи Стюарта формалізує і істотно спрощує розв'язання задачі синтезу складних динамічних систем та застосування для цього розробленої технології, представленої у [8]. Отримані структура та параметри головного регулятора системи керування рухом РП платформи Стюарта, який розподілений на три складові W_1, W_2 та W_3, сприяє поліпшенню рівень якості слідкування за вектором програмних сигналів і дозволяє врахувати перехресні зв'язки всередині платформи Стюарта, підвищує точності виконання заданої траєкторії за рахунок збільшення кількості ступенів свободи при виборі структури регулятора.

КЛЮЧОВІ СЛОВА: синтез, матриця передавальних функцій, слідкуюча система керування, функціонал якості, платформа Стюарта.

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